# 5th Tutorial of the DESIGN THEORY SIG

27th Jan – 29th Jan, 2021 in Paris

Special Interest Group on
**DESIGN THEORY**
*of the International Design Society*

the Design Society
a worldwide community

## BASIC COURSES

Design Theory:
history, tradition & contemporary challenges

Generativity

Knowledge Structure

Social Spaces

## ADVANCED COURSES

Biomimetic with design theory

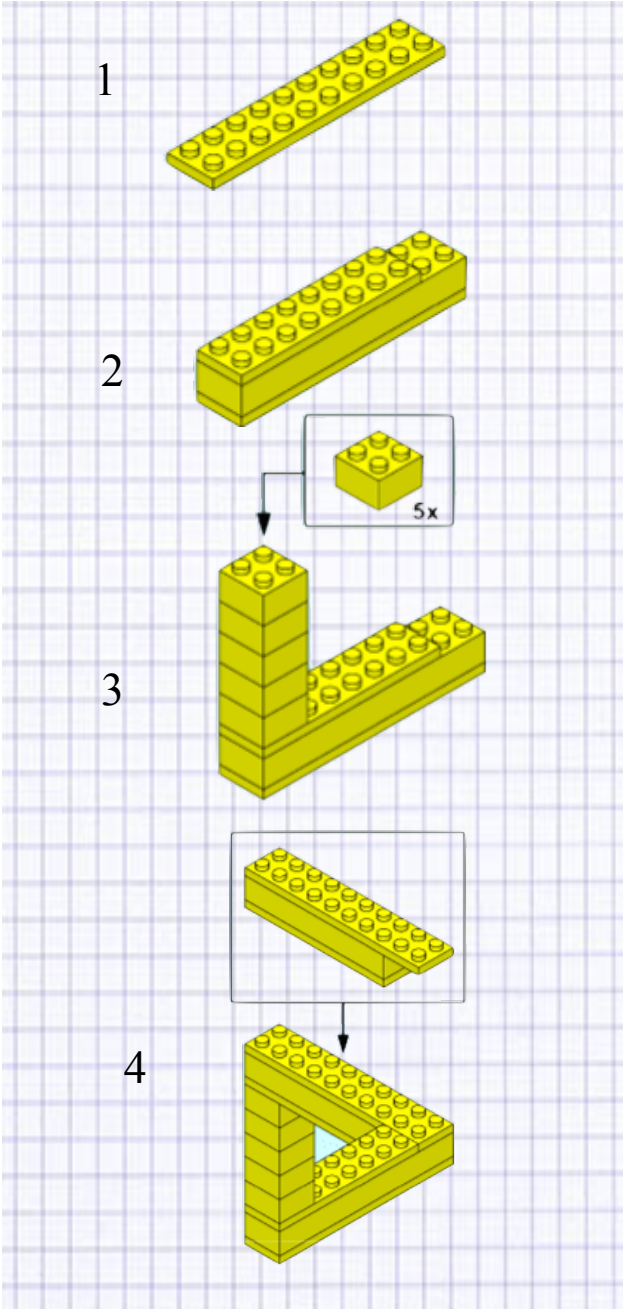
Parameter analysis method with design theory

Empirical analysis of failures in design

Automated search in digital innovation

Creativity & design theory

## BREAKOUT GROUPS :
## Explore your Thesis with Design Theory

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design theory and methods for innovation

institut interdisciplinaire de l'innovation

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PSL

# 5th SIG Design Theory Tutorial (27-28-29 jan 2020, Paris, France)

**Tutorial Faculty**

| Professorial College | | |
|---|---|---|
| **Name** | **Institution** | **Country, city** |
| Hatchuel Armand | MINES ParisTech | France, Paris |
| Kroll Ehud | ORT Braude College | Israel, Karmiel |
| Le Masson Pascal | MINES ParisTech | France, Paris |
| Reich Yoram | Tel Aviv University | Israel, Tel Aviv |
| Subrahmanian Eswaran | Carnegie Mellon University | USA, Pittsburg |
| Weil Benoit | MINES ParisTech | France, Paris |

**Organizer**: Maxime Thomas

**Speakers:**

| Speakers | | |
|---|---|---|
| **Name** | **Institution** | **Country, city** |
| Boudier Justine | MINES ParisTech | France, Paris |
| Brown Christopher | Worcester polytechnic institute | USA, Worcester |
| Gaetano Cascini | Politechnico di Milano | Milano, Italy |
| Fritzsche Albrecht | Ulm University | Germany, Ulm |
| Gericke Killian | Rostock University | Rostock, Germany |
| Hatchuel Armand | MINES ParisTech | France, Paris |
| Kroll Ehud | ORT Braude College | Israel, Karmiel |
| Le Masson Pascal | MINES ParisTech | France, Paris |
| Nagel Jacquelyn K.S. | James Madison University | USA, Harrisonburg |
| Reich Yoram | Tel Aviv University | Israel, Tel Aviv |
| Smulders Frido | TU Delft | Deflt, Netherlands |
| Subrahmanian Eswaran | Carnegie Mellon University | USA, Pittsburg |
| Weil Benoit | MINES ParisTech | France, Paris |

## Scientific background and goals

*The community of the Design Theory SIG of the Design Society, was created in 2007, to strengthen and unify the field of design theory. Since, thanks to active and fruitful research, important achievements have been reached through: a) historical and comparative work on design theories (Hatchuel et al. 2011; Le Masson, Dorst, and Subrahmanian 2013) b) establishing theoretical foundations with a high level of generality that consolidate Design ontology and paradigm (Hatchuel et al. 2018). Design Theory now offers a firm scientific body and ground for integrated and holistic engineering design (Vajna 2020). It has a growing impact on different disciplines in both natural and social sciences. Today, Design Theory is a vibrant research field that offers consistent models, tools and methodologies that PhD students may want to use to pursue their own research questions.*

*Therefore, the goal of this tutorial is two-folded. First, helping the students from different disciplines to master the literature, tools and methods of Design Theory for their own doctoral research. Second, presenting open questions and recent advances in Design Theory for PhD students willing to contribute to the field.*

*The tutorial attracts students from fields where Design Theory has now a rich literature:*

- *Engineering Design,*
- *Decision and rationality theory*
- *Psychology of Creativity*
- *Innovation Management,*
- *Knowledge and Science Management,*
- *Public Management and Policy making processes*

*It also welcomes students from Humanities, Philosophy and Art that are willing to investigate the implications of Design Theory in their fields.*

*To reach these goals, the tutorial provides the following contents:*

- *Basic courses: several modules, made by professors of the Professorial college, on basic notions of design theory*
- *Work with faculty members: interactive work sessions with the tutorial faculty members for students to identify what design theory can bring to their research*
- *Advanced Topic: short presentation made by an expert on an advanced topic in design theory – typically: 30 minutes, based on a paper, presented by a professor + 15 minutes for questions.*
- *Publishing in design theory: presentation of the Research in Engineering Design journal*

*Bibliography:*

Hatchuel, Armand, Pascal Le Masson, Yoram Reich, and Eswaran Subrahmanian. 2018. 'Design Theory: A Foundation of a New Paradigm for Design Science and Engineering'. *Research in Engineering Design* 29 (1): 5–21.

Hatchuel, Armand, Pascal Le Masson, Yoram Reich, and Benoit Weil. 2011. 'A Systematic Approach of Design Theories Using Generativeness and Robustness', 12.

Le Masson, Pascal, Kees Dorst, and Eswaran Subrahmanian. 2013. 'Design Theory: History, State of the Art and Advancements'. *Research in Engineering Design* 24 (2): 97–103.

Vajna, S. 2020. *Integrated Design Engineering: Interdisciplinary and Holistic Product Development*.

# Day 1: Room V111-112-113 / V114 / V115 / V116 / V119

| Basic Course | Advanced Topic / Paper Discussion | Breakout Groups |
|---|---|---|

| Day 1 – 27 Jan 2021 | | | |
|---|---|---|---|
| **Timetable** | **Type of Course** | **Title Course** | **Speakers** |
| 9:00 - 10:00 | **Workshop program + presentation of participants + Paper discussion** | Design theory: a foundation of a new paradigm for design science and engineering | Pascal Le Masson, Eswaran Subrahmanian Maxime Thomas |
| 10:00 - 11:00 | **Basic course:** Classical School | An overview on the Design Methodology by Gerhard Pahl and Wolfgang Beitz | Killian Gericke |
| 11:00 - 11:30 | **Break** | | |
| 11:30 - 12:30 | **Breakout groups (1/5)** | Exploring your thesis with Design Theory | Professorial College |
| 12:30 - 14:00 | **Lunch** | | |
| 14:00 - 15:00 | **Basic course:** Classical School | The simonian tradition in design (Economics, info, learning, decision, problem solving tradition) | Eswaran Subrahmanian |
| 15:00 - 16:00 | **Basic course:** Contemporary Formal Models I | Introduction to CK Design Theory | Pascal Le Masson & Benoit Weil |
| 16:00 - 16:30 | **Break** | | |
| 16:30 - 17:30 | **Advanced topic / Paper discussion (1)** | The Dreamliner's bumpy road to takeoff. Overlooked Design & Innovation Theory as root cause? | Frido Smulders |
| 17:30 - 18:30 | **Advanced topic / Paper discussion (2)** | Design theory and the art tradition | Armand Hatchuel |

# Day 2: Room V111-112-113 / V114 / V115 / V116 / V119

| Day 2 - 28 Jan 2021 | | | |
|---|---|---|---|
| **Timetable** | **Type of Course** | **Title Course** | **Speakers** |
| 9:00 - 10:00 | **Breakout groups (2/5)** | Exploring your thesis with Design Theory | Professorial College |
| 10:00 - 11:00 | **Basic course:** Contemporary Formal Models II | Enhanced parameter analysis method | Ehud Kroll |
| 11:00 - 11:30 | **Break** | | |
| 11:30 - 12:30 | **Breakout groups (3/5)** | Exploring your thesis with Design Theory | Professorial College |
| 12:30 - 14:00 | **Lunch** | | |
| 14:00 – 15:00 | **Basic course:** Contemporary Formal Models III | Knowledge structure in design (n-dim, category theory, matroïd, sp splitting condition) | Eswaran Subrahmanian |
| 15:00 – 16:00 | **Advanced topic / Paper discussion (3)** | Biomimetics with design theory (Vendôme classroom, visioconf) | Jacquelyn K.S. Nagel |
| 16:00 - 16:30 | **Break** | | |
| 16:30 - 17:30 | **Advanced topic / Paper discussion (4)** | Axiomatic Design for Creativity, Sustainability, and Industry 4.0 | Christopher Brown |
| 17:30 – 19:30 | **Cocktail** | | |

# Day 3: Room V111-112-113 / V114 / V115 / V116 / V119

| Day 3 – 29 Jan 2021 | | | |
|---|---|---|---|
| **Timetable** | **Type of Course** | **Title Course** | **Speakers** |
| 9:00 - 9:45 | **Advanced topic / Paper discussion (5)** | Demonstration of fixation effect during generation of creative ideas from fundamental experimentation approach to applied experimentations. | Justitne Boudier |
| 9:45 - 10:30 | **Advanced topic / Paper discussion (6)** | Design, Creativity and design Theory | Gaetano Cascini |
| 10:30 - 11:00 | **Break** | | |
| 11:00 – 11:45 | **Breakout groups (4/5)** | Exploring your thesis with Design Theory | Professorial College |
| 11:45 - 12:30 | **Breakout groups (5/5)** | Exploring your thesis with Design Theory | Professorial College |
| 12:30 - 14:00 | **Lunch** | | |
| 14:00 – 15:00 | **Advanced topic / Paper discussion (7)** | Conjunctions of Design and Automated Search in Digital Innovation | Albrecht Fritzsche |
| 15:00 – 16:00 | **Publishing in design theory** | Room V115 | Yoram Reich (RED) |

# Day 1: Room V111-112-113 / V114 / V115 / V116 / V119

| Basic Course | Advanced Topic / Paper Discussion | Breakout Groups |
|---|---|---|

| Day 1 – 27 Jan 2021 | | | |
|---|---|---|---|
| **Timetable** | **Type of Course** | **Title Course** | **Speakers** |
| 9:00 - 10:00 | **Workshop program + presentation of participants + Paper discussion** | Design theory: a foundation of a new paradigm for design science and engineering | Pascal Le Masson, Eswaran Subrahmanian Maxime Thomas |
| 10:00 - 11:00 | **Basic course:** Classical School | An overview on the Design Methodology by Gerhard Pahl and Wolfgang Beitz | Killian Gericke |
| 11:00 - 11:30 | **Break** | | |
| 11:30 - 12:30 | **Breakout groups (1/5)** | Exploring your thesis with Design Theory | Professorial College |
| 12:30 - 14:00 | **Lunch** | | |
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| 17:30 - 18:30 | **Advanced topic / Paper discussion (2)** | Design theory and the art tradition | Armand Hatchuel |

## Pascal LE MASSON

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Main research interests: design theory, design oriented organization, design and neurosciences, design economics, design and creation, design history.

## Eswaran SUBRAHMANIAN

Dr. Eswaran Subrahmanian is a Research Professor at the ICES and EPP at Carnegie Mellon University. He was the Chief Scientist at the Center for Study of Science, Technology and Policy (India, 2008- 2011) and has held visiting professorships at the Faculty of Technology and Policy Management at TU-Delft (Netherlands), the University of Lyon II; and the National Institute of Standards and Technology. His research is in the areas of Socio-technical systems design, Decision support systems, Engineering informatics, Design theory and methods, and engineering design education. He has worked on designing design processes and collaborative work support systems with Westinghouse, ABB, Alcoa, Bombardier, Boeing, and Robert Bosch. He is a founding member of a Bangalore-based non-profit research group, Fields of View, that uses simulation and gaming for inclusive design of urban issues. He is a Distinguished scientist of the Association of Computing Machinery and Fellow of the American association of Advancement of Science.

**Title of the Presentation:**

Design Theory: a foundation of a new paradigm for design science and engineering.

**Synopsis:**

This is the introduction of the Tutorial. We present contemporary issues of Design Theory. We show that the nature of contemporary innovation has deeply changed and requires design theory that accounts for generativity, the design of new definitions of objects, knowledge re-ordering and new social spaces.

**Main Reference:**

Hatchuel, A., Le Masson, P., Reich, Y., and Subrahmanian, E. (2018). “Design theory: a foundation of a new paradigm for design science and engineering.” Research in Engineering Design, 29, pp. 5-21.

**Further readings:**

Le Masson, P., Dorst, K., and Subrahmanian, E. (2013). “Design Theory: history, state of the arts and advancements.” Research in Engineering Design, 24, (2), pp. 97-103

Le Masson, P., Weil, B., and Hatchuel, A. (2017). “Introductory Chapter: Contemporary Challenges of Innovation-Why New Design Theories.” In: Design Theory - Methods and Organization for Innovation, Springer Nature pp. 1-18

Le Masson, P., Hatchuel, A., and Weil, B. (2017). “Design theories, creativity and innovation.” The Elgar Companion to Innovation and Knowledge Creation, H. Bathelt, P. Cohendet, S. Henn, et L. Simon, eds., Edward Elgar Publishing, Cheltenham, UK pp. 275-306

El Qaoumi, K., Le Masson, P., Weil, B., and Ün, A. (2017). “Testing evolutionary theory of household consumption behavior in the case of novelty - a product characteristics approach.” Journal of Evolutionary Economics

Le Masson, P., and Weil, B. (2013). “Design theories as languages for the unknown: insights from the German roots of systematic design (1840-1960).” Research in Engineering Design, 24, (2), pp. 105-126.

Res Eng Design (2018) 29:5–21
https://doi.org/10.1007/s00163-017-0275-2

ORIGINAL PAPER

# Design theory: a foundation of a new paradigm for design science and engineering

**Armand Hatchuel[1] · Pascal Le Masson[1] · Yoram Reich[3] · Eswaran Subrahmanian[2]**

Received: 27 October 2017 / Revised: 28 October 2017 / Accepted: 30 October 2017 / Published online: 10 November 2017


**Abstract** In recent years, the works on design theory (and particularly the works of the design theory SIG of the design society) have contributed to reconstruct the science of design, comparable in its structure, foundations and impact to decision theory, optimization or game theory in their time. These works have reconstructed historical roots and the evolution of design theory, conceptualized the field at a high level of generality and uncovered theoretical foundations, in particular the logic of generativity, the "design-oriented" structures of knowledge, and the logic of design spaces. These results give the academic field of engineering design an ecology of scientific objects and models, which allows for expanding the scope of engineering education and design courses. They have contributed to a paradigm shift in the organization of R&D departments, supporting the development of new methods and processes in innovation departments, and to establishing new models for development projects. Emerging from the field of engineering design, design theory development has now a growing impact in many disciplines and academic communities. The research community may play a significant role in addressing contemporary challenges if it brings the insights and applicability of design theory to open new ways of thinking in the developing and developed world.

**Keywords** Generativity · Design theory · Decision theory · Knowledge structure · Social spaces

## 1 Introduction

The value of design is today largely recognized, especially in its current manifestation of design thinking. Nevertheless, there are recurrent debates on its logics, its foundations and even its contemporary value as seen in professional forums such as LinkedIn. Dealing with design is difficult due to its fragmentation into different professions, the need to resist the drifts created by scientific fashions (Le Masson et al. 2013), and the need to fit continuously changing environments. There has been a recognition of the lack of unity and identity of the field—for instance, Margolin (2010) stated that research in design "remains equally cacophonous and without a set of shared problematics."

"A set of shared problematics" is precisely what design theory[1] as a field of study aims to define, or more precisely,

Pascal Le Masson and Eswaran Subrahmanian are the two co-chairs of the design theory SIG of the design society. Armand Hatchuel and Yoram Reich are the two founding co-chairs of the design theory SIG of the design society.

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[1] We do not define what design theory as a field of study is in this paper, or what a design theory is. We also do not precisely state what it means for design theory to function as a new paradigm for science. We assume intuitive interpretations of these important concepts and leave the rest for future elaboration, including by other members of the community. We also do not conduct a philosophical analysis of the (im)possibility or over-generality of design theory as we base our paper on significant body of work that demonstrates the possibility and value of design theory.

to design! As we see later, addressing any design issue requires a group of actors operating in a particular manner. Consequently, to address this need or even define it beforehand, the design society established a design theory (DT) special interest group (SIG) almost 10 years ago. Since its founding, work on this subject has accelerated, evolved and matured. This paper makes a synthesis of the progress of the collective endeavor of members of the DT SIG. It is not a review of all studies on the subject; in this sense, it is not comprehensive. As design theory is at the core of many design fields—industrial design, engineering design, architecture design and others, the work presented, could contribute to them also. Further, we show how design theory can contribute to the foundations of design as a new paradigm for design science and engineering.

To set the context of this paper, we first present the brief history of the DT SIG and some of its results. The DT SIG of the design society had its first meeting in Paris in 2008 with a little more than twenty participants from seven institutions. Eight meetings later, in 2015, the DT SIG attracted more than one hundred participants from 35 institutions. Currently, there are more than 300 people connected to the SIG community. Since its inception, the SIG operation has been led by a group of people deliberating at least annually about its past and future objectives and operation. The SIG has been opened to people from various disciplines and communities including not members of the design society in order to expand its diversity and reach out. These people have been invited to ease their entrance to the group. Understanding the context of the SIG is critical for two reasons. First, the core work on design theory involves designing theories; consequently, if we develop theoretical understanding about design, we should use it ourselves. It will turn out to be that the SIG started and has been evolved to precisely support the key ingredients underlying design that we will subsequently term ontology of design (i.e., generativity, splitting condition, and social spaces); in this way, the SIG has been practicing what we preach (Reich 2017). Second, and related to the first, the context tells readers which infrastructure is necessary to attempt a comprehensive study of design theory in case they wish to engage in such work.

In its deliberations and publications, the DT SIG has focused on different design theories, their history, their philosophical foundations, their formal models and their implications for design research, for society and for industry. In particular, the DT SIG re-visited classic design theories (e.g., Aristotle, Vitruvius, German systematic design, GDT, Suh's Axiomatic design, and modernist design) and discovered design theories in other fields (e.g., rhetoric, set theory). These studies have also led to an extensive assessment of the relationships between theories. For example, the explorations have established that when dealing with mathematics-based theories, the recent theories, and particularly C–K theory, are integrative of past theories and could serve as a platform for the development of new theories. There have been efforts to propose new theories or extension of theories, such as C–K/Ma (C–K theory and matroids), C–K and category theory, new parameter analysis, infused design and others. The design of the SIG has enabled collaborations outside the design community (e.g., collaborations with management, philosophy, psychology, cognitive science, history, physics, and mathematics). In effect, the DT SIG has grown as a social space for explorations in and sharing of efforts in design theory.

Any design activity, including that of design theory, involves creating new terminology to discuss it. This terminology is required to create common vocabulary, cognitive artifacts, to facilitate communication and sense making about the new properties of the new design (Subrahmanian et al. 2013). Similarly, this paper makes use of new vocabulary (presented in italic) developed or elaborated at the SIG in its journey. Examples or simple definitions are offered in the text but more detailed descriptions appear in the references literature.

The creation and sustenance of the SIG have been made possible by the constant support of industrial companies by funding the Chair of Design Theory and Methods for Innovation (Airbus, Dassault Systèmes, Ereie, Helvetia, Nutriset, RATP, Renault, ST-Microelectronics, SNCF, Thales, and Urgo). This support underlines that many companies—a spectrum of big corporate firms, small start-ups, or SMEs, in diverse industrial sectors—mobility services, aeronautics, automotive industry, energy microelectronics, healthcare, software—are keenly interested in the changing identity of objects,[2] of systems, and of values in our societies and our industries (Le Masson et al. 2010b). These companies have expressed the need for a design theory, as a body of knowledge and principles, to be able to invent organizations, methods and processes for contemporary issues in innovation (Hatchuel et al. 2015). This echoes the emergence of 'design thinking' as a slogan across engineering, sciences and management following needs to organize more innovative design processes [see, for instance, the Harvard Business Review issue on design

[2] The identity of object is defined through the perception of people organizing the word into categories of cognitive artifacts. Simplistically, it could be done by a set of properties or functions that people commonly associate with the object but it could be more complicated than that (Subrahmanian et al. 2013). For example a "phone" used to be characterized by its function of facilitating voice communication. Today, a "cellular phone" has very different identity than early cellular phones, marking its radical change of identify. Similarly, Uber started with the identity of a sharing economy brand, turning into a disruptive taxi company, and moving fast towards automated mobility in a form antithetical to its original identity.

thinking—September 2015; see also (Brown and Martin 2015)].[3]

In the past years, members of the SIG published approximately 80 papers on design theory in leading journals such as Journal of Engineering Design, Research in Engineering Design, Creativity and Innovation Management, Journal of Creative Behavior, and others. In this paper, we do not give a detailed overview of the entirety of this body of work, nor are we trying to present in detail a particular design theory. Our attempt is to state theoretical claims about what is required of a particular design theory for which there is ample evidence in the referred literature. Consequently, we do not offer here new evidence but rely on previous studies and here provide a synthesis of core ideas. We will focus on what these design theory papers reveal as an ontology of design (part 1), and we will then show the consequences of this framing for the academic research on design (part 2), and for design in industry (part 3).

It is clear that a broad and central topic such as design theory elicits many questions like a domino effect; for example, what is the role of design theory in design science? Can design theory be too abstract to be useful? Can logical inference such as induction or abduction be considered as design? Is analogy, metaphor, or blending forms of design? Or what is creativity? Each such question deserves a separate study. Some of the issues have been touched by the referenced literature and others are open. We hope that the ideas presented will sprung new studies including using the concepts presented here to analyze old and new claims about design and related topics in more precision.

## 2 Design theory: a clarification of an ontology of design

To understand what the nature of design is, what differentiates it from other activities, and subsequently to support it, we need to engage in design theory and a major outcome of such work would be the ontology of design.

### 2.1 Extending classical models of thought

The significant body of current work on design theory helps clarify the ontology of design—see for instance the special issue on design theory in Research in Engineering Design (Le Masson et al. 2013). The question of ontology raises basic issues. For instance, what is a design task? Paradoxically it is far from self-evident—a design "brief" (to take the word of industrial designers) is more than a problem—it is even more than ill-defined or wicked problem. For example, "smart objects for well-being," "green aircraft," "resilient robots," and "low cost cars," are in effect only propositions on artefacts that are desirable but partially unknown. They are highly underdetermined both from a framing and solution seeking perspectives.

If so, what is the scientific identity of design (or the identity of the object design)? Let us take an example. Suppose that the brief is: "reduce 20% of the costs of a refrigerator." The new design can be done by optimizing: optimize specifications, optimize conceptual models, embodiments, components, supply chain, production, etc. In this optimization process, if "unknown" is limited to the uncertainty on the value of well-known design parameters, then adaptive planning will be required to overcome the uncertainty. In this optimization process, the goal is to reduce uncertainty—hence, design appears as a form of decision making under uncertainty.

If we change the "unknown" to be the exploration of unknown design parameters, the search includes exploring new scientific results, new components and technological principles. In this process, the unknown has to be structured and elaborated for it to be generative. The strength and uniqueness of design are in its generativity:[4] the ability to conceptualize and create non-existent alternatives. Design being an act to change the state of the world including with new unknown alternatives requires a design theory to account for generativity. We claim that generativity is an essential ontological property of design that provides it with a unique scientific identity.

### 2.2 The case for generativity in an ontology of design

With the simple example below, we contrast the two types of unknowns in design, not in opposition to each other, but to make the case that the ontology of design, the science of design, should cover the entire spectrum from decision making to include the strong condition of generativity. Consequently, design has some of its roots in well-known formal models such as decision making under uncertainty (Savage 1972; Wald 1950; Raïffa 1968), problem solving

[3] Note that design thinking is today a particular design practice that insists on prototyping and user knowledge. Design theory corresponds to a scientific program that can account for the logic and performance of design thinking in specific cases, see (Le Glatin et al. 2016).

[4] Note that as we explain later, generativity is different from the general notion of an ability to generate or create. It has clear definition as well as formal description that could be found in references such as (Hatchuel et al. 2011a, b, 2013b). This definition makes our generativity different from the word 'generative' that is used in generative design grammars or even in different disciplines such as generative grammar in linguistics.

(Simon 1969, 1979, 1995) and combinatorics (e.g., planning, graph theory). However, design theory cannot be limited to these models as they only address the first form of unknown where the parameters are known within a problem framing; and there are no unknown parameters leading to changes in the parameter set.

Let us illustrate the issue with three simple "anomalies" with traditional formal models:

#### 2.2.1 *The "raincoat-hat" anomaly in decision under uncertainty*

Derived from Wald and Savage's work on decision theory under uncertainty, Raïffa developed decision theory under uncertainty (Raïffa 1968). Given a set of alternatives, the states of nature and the beliefs on these states of nature, it is possible to compute the expected utility of each alternative and choose the best one. This is the basis for the techniques of investment evaluation and decision and for portfolio management. For instance, in case of choosing the best accessory to go out for a walk, the decision alternatives are "choose a raincoat" ($d_1$) vs. "choose a hat" ($d_2$); the states of nature are "sunny weather" vs. "rain"; the a priori probabilities on the states of nature are 50% for "sunny weather" and 50% for "rainy weather;" and the utility for walking in the rain with a raincoat is 100, for walking in the rain with a hat is 10, for walking in the sun with a raincoat is 10, and for walking in the sun with a hat is 100. The beauty of the theory of decision making under uncertainty is its ability to identify the "optimal" decision (maximize the expected utility) and to compute the value of a new alternative ($d_3$) that enables to reduce uncertainty on the states of nature taking into account the reliability of a new information (hence, the utility of listening to weather forecast before going out for a walk, knowing that weather forecast is reliable four times out of five).

An anomaly emerges when the issue is not to find the optimal alternative among known ones but to generate (to design) a new alternative such as "an alternative that is better than a raincoat in the rain and better than a hat in the sun." This "alternative" is partially unknown (as such it is not an alternative as $d_1$, $d_2$ or $d_3$) and still it is possible to build on it: it has a value for action! For instance, it can push to explore on uses in mobility, on textiles, on protecting against rain, etc. It is even possible to compute elements of the value of this solution—not as a result but as a target: to be acceptable, the value distribution of the solution should be, for instance, 100 in each case. Decision theory under uncertainty cannot account for this kind of situation. Design theory needs to address this anomalous case of design behavior with respect to decision theory.

#### 2.2.2 *The "barometer" problem*

The work on problem solving and on algorithms to construct solutions to complex problems went as far as finding algorithms that play chess better than the best human being—on May 11, 1997, Deep Blue software won world Chess champion Gary Kasparov. But let us consider the following "problem." The story says that, for an oral exam, a physics professor asked the following question to a young student (said to be Nils Bohr, which is actually not true and not important for our point): "how can we measure the height of a tall building using a barometer?" The professor expected a solution based on the relationship between pressure and altitude. And recent AI algorithm would probably be able to find that relation and use it for measuring the height of the building (see recent success of IBM Watson software at Jeopardy game).

In contrast, the student proposed many other solutions like: "Take the barometer to the top of the building, attach a long rope to it, lower the barometer to the street and then bring it up, measuring the length of the rope. The length of the rope is the height of the building." Or: "take the barometer to the basement and knock on the superintendent's door. When the superintendent answers, you speak to him as follows: "Mr. Superintendent, here I have a fine barometer. If you tell me the height of this building, I will give you this barometer." The "problem" was well-framed and should have been solved in a direct way, relying on known laws and constraints. But the student actually ignored the implicit directives embedded in the instrument and, consequently, addressed the "problem:" "measure the height of a tall building using a barometer—without measuring pressure." From a problem solving perspective, he adds a constraint ("without measuring pressure") and designs an expanded solution space that relies on properties of the objects that are out of the frame of the problem: the barometer is not only a system to measure pressure, it also has a mass, it has a value, etc. In innovation as well, the innovator will play on neglected dimensions of objects or even invent new dimensions of objects, changing their identities—like smartphone functions that are not limited to phone calls. This example is an anomaly from a problem solving perspective that needs to be accounted for in a design theory.

#### 2.2.3 *The "Escher-Lego"*

The works in combinatorics have led to master more and more complex combinations, for instance, through AI, expert systems, neural networks or evolutionary algorithms. These models combine elements of solutions into comprehensive solutions; they evaluate each solution according to an objective function and depending on the performance, they recombine the elements of solutions. Just like problem

solving or decision making, these models are heavily used in industry (e.g., image or speech recognition, or contemporary CRM through targeted ads). In this model, Lego appears as the archetype of the combination logic—all blocks can be combined and it is possible to evaluate the final solution. Lego building can be more or less efficient or even "original:" the combinations are more or less sophisticated, refined, etc., inside the algebra of all possible combinations. This idea is embodied in product concept or architecture generation (Ziv-Av and Reich 2005) or generative languages such as shape grammars and patterns, especially in architecture (Stiny and Gips 1972; Flemming 1987).

Playing with this "Lego" paradigm, the Swedish photograph Erik Johansson has been revisiting M. C. Escher 'impossible construction' (Fig. 1). In particular, he created a shape that is done with Lego blocks but is impossible with (physical) Lego blocks. This picture illustrates in a very powerful way the limit of the combinatorics models for innovation: in a world of Lego, many combinations are possible, but the innovator might go beyond such combinations by creating something that is made with Lego but is beyond all the (physical) combinations of Lego. Innovation can be like this: combining old pieces of knowledge so as to create an artifact that is of course made of known pieces but goes beyond all combinations of the known pieces by breaking the rules of composability. The problem has been transformed, allowing for new avenues of generativity. Here again, this example seems clearly beyond classical combinatorics—but design theory should be able to address it.

In the above three examples, we illustrate the need for a basic requirement for design theory: design theory has to extend classical models of thought on designing to account for these anomalies. We claim that design theory contains decision, problem solving, observation, perception, yet in an interaction, not in opposition, with another language, a language of emergence, of unknowness, or more generally of "desirable unknowns."

Usual models of thought such as decision making, problem solving and combinatorics are characterized by an optimization rationale, by integrated knowledge structures and by a "closed world" assumption. Clarifying the ontology of design essentially consists of answering: (a) what is this rationale that encompasses optimization but goes beyond it—(generativity); (b) what is the knowledge structure that encompasses integrated knowledge structures but goes beyond them (splitting condition); (c) what is the social space that encompasses "closed world" assumption but goes beyond it (social spaces). The work done on design theory in the last decades to address these three points arrived at an ontology of design that is integrative.

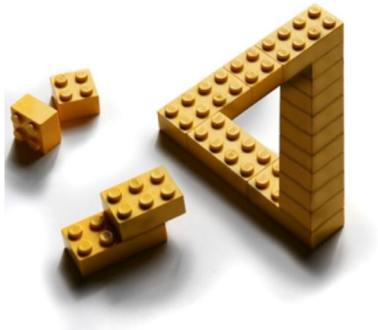

**Fig. 1** Escher Lego—Erik Johansson

### 2.3 Defining and modeling generativity: a rationale for an extended design theory

The literature on innovative design has long been trapped in the opposition between decision theory (e.g., optimization, programming, or combinatorics) and creativity theory (ideation), i.e., rigorous and formal reasoning on the one hand vs. psychological phenomena on the other hand.

Design theory today precisely enables to overcome these classical oppositions. Design theory shows that design is about another capability, which is neither decision, nor creativity. Design is about generativity which is defined as the capacity to generate new propositions that are made of known building blocks but are still different from all previously known combinations of these building blocks (Hatchuel et al. 2013b). Generativity is different from decision and different from creativity:

- Regarding decision making: generativity is different from the basic reasoning in decision making and programming, namely deduction—precisely because the issue is to account for the emergence of a proposition that cannot be obtained by deduction from known building blocks (see the works on the limits of Simonian approach of design (Schön 1990; Dorst 2006; Hatchuel 2002; von Foerster 1991; Rittel 1972). Note that generativity is also different from abduction: let us start with Peirce's definition of abduction as in the Stanford Encyclopedia of Philosophy (SEoP 2017):

  The surprising fact C is observed,
  But if A were true, C would be a matter of course;
  Hence there is reason to suspect that A is true.

One of the observations of Peirce's abduction is that it did not invent a hypothesis but adopted a hypothesis.[5] Peirce was agnostic about where the hypotheses, A, came from

[5] This could be the reason why abduction works for diagnosis where one adopts a hypothesis or a set of hypotheses in identifying the cause of the symptoms and is confirmed or refuted by the available and new evidence. For comprehensive treatment of abduction and diagnosis see (Josephson and Josephson 1996).

and was primarily addressing scientific theories. However, design is not about explaining a new fact; it is about addressing a problem often outside the purview of what is typically done. Peirce's notion of abduction is not sufficient for understanding the complexity involved in designing or from where new or unknown objects came from. In their attempt to create a logic of design, Zeng and Cheng (1991) also make the case that problem–solution interaction requires a recursive logic that is beyond any of the traditional forms of reasoning including abduction as was proposed by March (1964). A compelling summary against the rationalist and cognitivist thinking alone is provided by Gedenryd (1998); his argument is that they are directed at the intra-mental cognitive model (deduction, induction and abduction) that ignores the interactive inquiry that is integral to design. Further elaboration of this topic is beyond the scope of the paper.[6]

- Generativity is also different from creativity (Le Masson et al. 2011). Creativity is about ideation, and ideation within existing bodies of knowledge. In ideation, one may have a very creative idea on one object—"a Ferrari that looks like an UFO"—without having the knowledge to generate this idea. Generativity includes also the capacity to create one or several entities that fit with the creative idea. Generativity includes knowledge creation and inclusion of independent knowledge from outside the current known knowledge (hence research). It also includes the impact of a new entity on the others and, more generally, the necessary knowledge re-ordering that is associated with the emergence of new entities. Generativity includes ideation whereas ideation does not include generativity.[7]

Design theory actually studies the variety of forms of generativity [for a synthesis, see (Hatchuel et al. 2011a, b)]. It has been shown that the historical development of design theory in 19th and 20th century is characterized by a quest for increased generativity (Le Masson and Weil 2013). The study of formal models of design theory such as general design theory (Tomiyama and Yoshikawa 1986; Yoshikawa 1981; Reich 1995), axiomatic design (Suh 1978, 1990), coupled design process (Braha and Reich 2003), infused design (Shai and Reich 2004a, b) or C–K design theory (Hatchuel and Weil 2003, 2009) has also shown that they can all be characterized by their capacity to account for a form of generativity. The theories have progressively evolved to become independent from professional languages and professional traditions; e.g., the theories are valid for technical language, as well as functional one, or emotional one, and their universality enables to integrate the constant evolutions of these specific languages. They rely on abstract relational language such as "proposition," "concept," "desire," "neighborhood," "duality," etc. The generativity grows from one "new" point in a complex topological structure to the generation of new propositions with a generic impact—i.e., new definition of things, new categories, new "styles," and new values. The theories step out of the combinations and enable to rigorously change the definitions and the references.

C–K theory is one illustration of generativity as the central theoretical core of a design theory (Hatchuel et al. 2013b). In C–K theory, design is modeled as the generative interaction between two logics of expansion: the knowledge space is the space where propositions with a logical status expand (through learning, exploration, scientific experiment, deduction, social assessment, etc.); and the concept space is the space where linguistic constructs in design that are partially unknowns can also be structured in a rational way [with a specific structure—tree structure created by the partition operations; relying on semantic operations such as "living metaphors" (Ricoeur 1975)]. Both spaces are expansive, both spaces "generate" and "test"—but not with the same logic. And the two expansive processes are intertwined in C–K interactions. Concepts lead to knowledge expansions and Knowledge leads to concepts expansions.

Actually, this generic core is present in all models of design theory. For instance the systematic approach of engineering design (Pahl et al. 2007) consists in expanding knowledge (knowledge on existing objects and phenomena: knowledge on functional models, on conceptual models, on embodiment models, on machine elements, etc.) and expanding the alternatives on the still unknown and emerging object (alternatives on functional definition of the emerging object, on the conceptual definition of the emerging object, etc.). Note that this implies a double meaning of functional language (functions of the known objects and functions of the unknown object) that explains formal issues with functions (Vermaas 2013). The same generative process appears in function–behavior–structure model (Dorst and Vermaas 2005; Gero 1990) or in Zeng's product design theory (Zeng and Gu 1999a, b), which models evolutionary design processes. Several studies have analyzed in detail the generative core in design models and methods, by casting these methods and models in formal design theory framework—see for instance (Shai et al.

[6] But see recent attempts to define abduction in a way that is more akin to design (Kroll and Koskela 2017). See also the very interesting work on abduction and design theory in Sharif Ullah et al. 2011.

[7] We contend that models of analogy such as those presented in Goel (2013) that lead to the creation of new objects and their elaboration have generative power. Consequently, different analogical inferences could be evaluated on their generativity, rather than on their capacity to create novelty, value and surprise that are context dependent.

2013; Kroll et al. 2014; Shai et al. 2009b; Reich et al. 2012).

The underlying hypothesis of design as generative is embedded in the *n*-dimensional information modeling project (*n*-dim). The project was conceived with design as creation of, interactions between, and use of sublanguages and knowledge structures arising from within and across domains and their evolutionary mapping. The underlying knowledge structures are mobilized in the creation of a new theory of the artifact with a new set of unknowns (Reich et al. 1999; Monarch et al. 1997; Subrahmanian et al. 1997). The *n*-dim approach, by virtue of supporting design knowledge structuring, provided a substrate for generativity from conception to realization of the artifact.

Generativity appears as a unique feature of design theory. This has critical consequences for research: it helps us answer the critical question of the validity of design theory. Is a design theory true or false? The answer is the same as in every science: a relativity principle is necessary to establish truth. In physics, theory of Newtonian mechanics is true for relatively low speed (relatively to the speed of light). For design theory, the relativity principle is the degree of generativity of a design process. A design theory can be true for processes with limited generativity and false for higher degree, true for routinized design and false for innovative design. And design theories can be ordered following their degree and form of generativity. Still no one knows today if there is a limit to generativity![8]

In industry, one could be tempted to say that strong generativity is rather at the beginning of industrial projects of new product development and low generativity is at the end of new product development processes. Still this assessment can be discussed in a long-term perspective: it appears that social networks and groups began with low collective generativity and were able to invent such sophisticated organizations like engineering departments, design departments or research labs (in the 19th and 20th century) to increase the overall generativity of a society (Le Masson and Weil 2013). And today, some industrial partners begin to consider that they need design theories that fit with high generativity levels or they realize that social and institutional generativity is critical in addition to disciplinary knowledge generativity (Meijer et al. 2015; Reich and Subrahmanian 2015, 2017).

[8] Note that there is no value judgement here but the observation that different theories need to be scoped well and could be evaluated based on their generativity. There is no attempt to discount any theory as different theories may be better in particular cases, similarly to other methods (Reich 2010).

### 2.4 Splitting condition: knowledge structures in design and the value of independence

The works on generativity as a core of design reasoning led to a surprising result: there is a formal condition of generativity. We tend to think that generativity is only constrained by cognitive fixations and does not depend on knowledge structures. But models of design theory have led to clarify that the generation of new propositions obeys a formal condition. This condition was initially identified by mathematicians studying forcing, which is a model of the design of new models of sets in set theory (Cohen 1963, 2002; Hatchuel et al. 2013b). They have shown that Forcing enables to create new sets and new models of sets by extension of known models of sets, and there is a formal condition for these new sets to be different from every already known set. The structure of knowledge related to the initial model of a set has to follow the so-called "splitting condition" (Jech 2002; Dehornoy 2010; Le Masson et al. 2016b).

Informally, splitting condition means that a new proposition is different from all the already known propositions if there is no determinism and no modularity in the knowledge structure. This actually corresponds to two critical properties of a knowledge structure in design:

- No determinism means that the new design is not directly determined by initial knowledge—or: design is not limited to "know how," it requires "new knowledge."
- No modularity means that the new design is not a modular instance of old designs—or: design is not limited to Lego; it requires "new concepts."

The splitting condition can be interpreted as a "negative" condition: without a "splitting condition" in the knowledge structure, there is no generativity. Note that such condition is a classic property of formal models of thought; for example, in decision theory, rules and domain-specific scoped ontologies are the necessary conditions for running algorithms and building decision functions.

But the splitting condition can also be interpreted in a more "positive" way: one can imagine providing the designer with a knowledge structure[9] that meets the splitting condition. Generativity increases when determinism is broken (a new independent alternative is created) and modularity is broken (adding the previously "modular" component is not indifferent anymore, it creates significant differences, it creates new independences). This creation of favorable new knowledge structures is illustrated by the *n*-dim approach to design support systems (Subrahmanian

[9] Knowledge structure here is meant to signify a body of knowledge that heretofore is not integrated. For example, user interaction studies bring new knowledge structures to interactive software design.

et al. 2003; Dias et al. 2003; Reddy et al. 1997; Reich et al. 1999) or the logic of biomimetic for stimulating creation (Freitas Salgueiredo and Hatchuel 2016).[10]

More generally, splitting condition underlines the value of independences in a knowledge structure: propositions that cannot be deduced from past ones and can add significant dimensions to an artefact. Splitting condition offers a completely new way to understand what knowledge structure is: the value of knowledge is not only in rules, ontologies, variants, algebra and integrated structures; it is also in the independences in knowledge structures.

Note that the value of independences is quite contradictory with the usual common sense coming from information theory. In information theory, one expects that a variable $X$ will enable to learn on a variable $Y$—hence, one expects that $Y$ and $X$ are strongly correlated. Or, conversely: in information theory, if $X$ and $Y$ are independent, then it means that $X$ does not bring any information on $Y$ hence $X$ is useless to $Y$. In contrast, splitting condition actually corresponds to the fact that if $X$ and $Y$ are independent, then $X$ can bring significant original information to design a new $Y$.

This curious condition of generativity has interesting industrial applications. Consider Plumpynut—a product developed by Nutriset, an innovative design company in France. This product saved millions of children in Africa. It was a true breakthrough because it was prepared in such a way that the child could be fed without the help of any nurse or doctor. This breakthrough was made possible by connecting three knowledge areas: nutrition (knowledge on malnutrition disease), user-driven analysis, and food-processing expertise. Three knowledge areas that were initially independent and the designers were able to connect them onto a single artifact (Agogué et al. 2015b). Given that such independent knowledge usually resides with different professionals, improved generativity leads to favoring extended participation in development projects (Reich et al. 1996).

Or consider the design of technologies, which is an area that is still poorly understood today: the design of a technology that is generic consists in linking previously independent application areas. One of the most well-known generic technologies is the steam engine; what is the specific breakthrough that made it become generic? It was not the use of steam (it was already known by Newcomen in early 18th century) and not even the separate condensation chamber invented by Watt in 1763 to improve the so-called "pumping engine" for mining. The breakthrough was a cinematic mechanism, invented in 1784, that enabled the transformation of linear movement into a rotary one that was invented in order to connect steam engine to the whole machine tool industry (and later to other applications areas) (Le Masson et al. 2016a, 2015). Hence, this example shows how design consists of changing independences in knowledge structures.

The analysis and evolution of independence in knowledge structures are one of the key parameters to understand the critical basis of breakthrough technological projects (Lenfle et al. 2016).

Finally, the lesson of the splitting condition is, more generally, that design is not only about idea generation but also is about knowledge structures. This observation has direct implications for teaching: do we teach "splitting" knowledge in our engineering courses? Do we teach how to enable a "splitting structure" in students' knowledge base?

### 2.5 Social spaces in design: the third element of the ontology

The engine of generativity combined with knowledge structures following the splitting conditions implies a strong design capacity and, hence, a significant dynamics of the designed artefacts. This observation has been confirmed by recent measurements of the evolution of functional definition of consumer products such as mobile phone, vacuum cleaner, iron or GPS navigation systems (see Fig. 2 extracted from El Qaoumi et al. 2017). These trends were derived using data from consumer report archives, which regularly study the main functional characteristics of a product, from a consumer point of view. As one would expect, over time the functions of a smart phone evolve strongly; since the first mobile phone comparative test in 1996, more than 110 new functions have emerged. Hence, the "identity" of the mobile phone, the properties that make the object 'a mobile phone' and distinguish it from others, from the consumer point of view, has significantly evolved. More surprisingly, the same phenomenon is true for GPS, and iron or vacuum cleaner. As observed, the nature of contemporary design dynamics is clearly "visible" on contemporary objects. Note that this observation strongly contradicts one of the most classical hypotheses of orthodox economics, namely Lancaster's hypothesis that a product type keeps the same functions (only the level and combinations were supposed to evolve) (Lancaster 1966a, b; El Qaoumi et al. 2017).

These generativity phenomena are not limited to products; the design logic extends to technologies, including chemical engineering (Potier et al. 2015), living organisms and ecosystems (Berthet et al. 2012), laws, regulations, software, psychological therapies (Imholz and Sachter

[10] Biomimicry is a recent area that builds upon at least two distinct disciplines such as engineering and biology and allows the creation of new knowledge structures to bridge them (Goel et al. 2014; Cohen and Reich 2016). It was shown that Design Theory such as C-K theory is a strong support to teaching biomimicry in engineering (Nagel et al. 2016).

2014) and, even to institutions (Le Masson et al. 2012b). As we have noted, design includes design of knowledge structures and since knowledge structures are deeply linked to social relations, it implies that design includes the design of new social spaces as identified by (Reich and Subrahmanian 2015, 2017). We can conclude that generativity in objects and evolving knowledge structures are necessarily related to specific social structures. With the two first elements of an ontology of design, namely generativity and independence in knowledge structure, follows an ontology of design spaces. This ontology includes social and institutional structures that span the variety of contexts where design takes place; it allows representing situations where design fails and those where it succeeds with respect to the two other ontological elements. In contrast, an ontology of decision theory leads to specific social structures that assume integrated knowledge structures leading to stabilized rigid institutions whose evolution is constrained by path dependence. Any ontology based on generativity and independences in knowledge structures requires open forms of social spaces and extended participation. Composition of social spaces that have independent knowledge sources satisfies the ontological concept in design theory: "splitting."

As a consequence, design helps us to rethink social figures such as consumer, technical colleges and institutions. They can now be characterized by their generativity and independence in knowledge structures! This is illustrated by the extraordinary organization of the International Technology Roadmap for Semiconductor (ITRS). This institution has organized the whole semiconductor industry ecosystem (chipsets designers, manufacturers, technology suppliers, research labs, universities, etc.) to be able to follow Moore's law for more than the last 20 years. Surprisingly enough, it is a completely open organization, the "roadmaps" are free and open, available to everybody; the organizational logic is never based on choice and selection

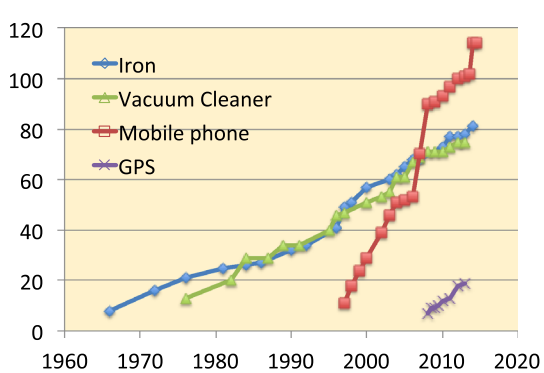


**Fig. 2** Cumulative number of new functional characteristics that a product type acquires over time, for 4 types of products, based on the data from the archives of French Consumer Report "Que Choisir" (Source: El Qaoumi et al. 2017)

of technological alternatives—as underlined by one organizational motto "we are not picking winners or losers." In ITRS, there are strong organizational and institutional rules. These rules, instead of provoking famous "lock-in" effects, are all oriented towards "unlocking" (Le Masson et al. 2012b).

The example also underlines that design theory is hetero-disciplinary: as articulated by Reich and Subrahmanian at the 2014 design theory workshop of the design theory special interest group. Further, their claim that design is "multi-scale" and "multi-phenomena," crossing the borders between materiality, social, and economics, is in complete coherence with the (historically) perceived features of design, since Vitruvius and the debates on the status of architects, designers and engineers in society. In spite of this inherent complexity, it is important to align technology or product knowledge structures with the social space and the institutional rules and cultures to create the right ecosystem for successful design (Reich and Subrahmanian 2015). In the recent work on measuring the economic complexity of countries, Hidalgo and Hausmann (2009) use a measure of the complexity of the products produced by a country to conclude that the propensity to create complex products (generativity) is determined by the availability of independent breadth of knowledge structures (splitting condition) and social capabilities and institutional structures (social spaces). This observation supports the proposition of this paper that generativity, splitting condition and the social spaces as ontological elements of a design theory provide us with a basic understanding of design at different scales from an individual to a firm to a country. Further, with these ontological elements, we should be able to analyze the methods in design and policy for their generativity (Hatchuel et al. 2011a, b).

To conclude: the work reported in the last decades has enabled us to clarify the ontology of design (Fig. 3). The rationale of design is generativity, and it extends the optimization rationale; characterization of independence of knowledge structures goes beyond the issue of integrated knowledge structures (one of the critical conditions for decision making, programming or problem solving); the open social spaces of design that can be themselves designed, thereby requiring design to embrace an "open world assumption," going beyond the decision social spaces that rely on a "closed world assumption."

This ontology calls for some comments:

- This ontology leads to a claim for design: design is a unique science that has, as a paradigm, the study of generativity.
- Design extends the historical paradigm of decision making. It paves the way to a second generation of

works that may investigate the models of decision processes that support generativity.

- In this ontology, design issues like "robustness," "system engineering," "conceptual design," or "modularity," can be addressed relying on the "relativity" principle of design, namely support of more or less generativity. At a low level of generativity, these issues are addressed in a decision framework and at a higher levels of generativity, these issues will be addressed with more generative models of design theory. For instance, modularity issues can be addressed with a given set of modules; or research on modularity can consist of designing new modules with specific properties enhancing generativity. For instance, one can study the stability and invariants of a given engineering system; or one can study how an engineering system can generate new objects and shapes. In the latter case, it appears that usual features of engineering systems (e.g., complexity, unpredictability, self-organization, networks and polycentricity, active and intelligent agents) can be made to follow the splitting condition, so that an engineering system might actually enable a strong generativity.

We now turn to an analysis of what the proposed ontology of design brings to the design science community. We first analyze the implications of design theory for academia and then the implications of design theory for industry.

## 3 Implications of advances in design theory for academic research and industry

### 3.1 Design theory for academic research

Design theory contributes to the foundation of a new paradigm for research in science, art and engineering.

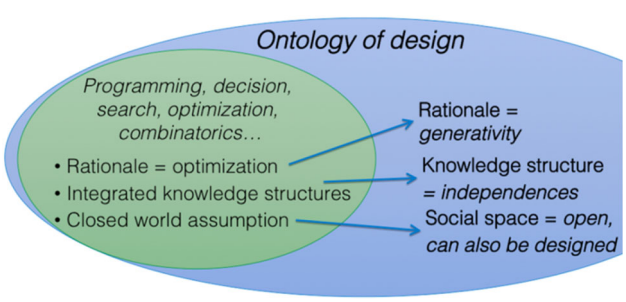


**Fig. 3** The ontology of design as an extension of the ontology of decision-optimization

#### 3.1.1 *Connecting different traditions and academic fields (art, science, engineering)*

Generativity and splitting condition might seem very abstract but they still lead to theoretical predictions. One could look at the domains that seem the more generative and see whether they follow the splitting condition. Where does generativity appear in our societies? For instance, let us take the recent study of practices of teaching art and industrial design at Bauhaus, being one of the most famous industrial design schools that has influenced contemporary pedagogy in industrial design. The prediction was: given the demonstration of generativity by Bauhaus students, one might expect that courses enabled students to acquire a knowledge structure that follows the splitting condition. The validity of this hypothesis was illustrated in (Le Masson et al. 2016b). The paper shows that Bauhaus professors such as Klee or Itten taught highly abstract design theory and knowledge structures to allow the generation of "new styles for the society of their age." The paper also shows that, by contrast, the pedagogy of engineering design in that period of time focused on "non-splitting" knowledge structures, precisely to prevent the constant revision of the definition of objects and to preserve a stable algebra of machines.

Relying on contemporary design theory, it was possible to also identify the logic of generativity in engineering design and engineering science (Le Masson and Weil 2013). It appears that engineering design theory frees the engineering designer from fixated relationships between functions and organs. Performance, functions, use cases, and specifications are languages to formulate unknown combinations and hence promote generative processes. On the other hand, knowledge structure is regularly re-ordered to integrate conceptual changes or to allow constant regeneration with limited re-ordering (Dias et al. 2003). The organization of machine elements, organs and, engineering models is reviewed, revised, and evolved regularly.

Design theory connects industrial design and engineering design. It also connects scientific discovery. As it is well known in contemporary epistemology, there is no direct link between observations and discoveries—design theory helps to describe how, in this interplay between discovery and observations, new concepts are designed (Hatchuel et al. 2013a; Shai et al. 2009a; Reich et al. 2008).

As a consequence, contemporary design theory strengthens research that studies generativity in science, art and, engineering.

#### 3.1.2 *Open new theory-driven experimental protocols*

A second consequence of advances in design theory is the increased capacity to build theory-driven experimental

protocols. Without clear theoretical framework, there is a danger of general inconclusiveness in experimentation—this was for instance the case in the multiple experiments conducted to know whether examples tend to fix or de-fix ideation processes. Based on design theory, researchers were able to formulate specific hypotheses (fixing example is the one formulated by restrictive design reasoning while de-fixing example is the one formulated by expansive design reasoning), provided techniques to enrich the scope of experiments to arrive at a clear conclusive results (Agogué et al. 2014).

More generally, design theory has explained and/or could have predicted a large variety of phenomena and enabling experimenting with them. For instance, Taura, Nagai and colleagues tested how concept blending and dissimilarity corresponded to different forms of creativity (Nagai et al. 2008; Taura and Nagai 2013). Eris characterized experimentally a type of question that appeared as specific to design activity—namely generative design questions (Eris 2003, 2004). Mabogunje and Leifer (1997) worked on the emergence of new nouns by recording noun-phrase in design exercises. Design theory also helps to formulate hypotheses and follow experiments based on the specific types of media like "non-verbal" media (sketching) (Brun et al. 2015; Tversky 2002). Experiments confirmed the differences resulting from specific forms of design reasoning between design professions (Savanovic and Zeiler 2007; Agogué et al. 2015a). In brainstorming experiments, design theory predicts the low generative power of brainstorming: theory predicts that the quantity of ideas is not related to originality and quality as originality is also *K*-dependent; it also predicts that focusing on de-fixing concepts generates more new knowledge and, hence, more original ideas and design value come from the consistent use of this new knowledge (Kazakçi et al. 2014).

#### *3.1.3 Stimulate new connections with contemporary mathematics and logic*

A third consequence of advances in design theory is to stimulate new connections with contemporary mathematics and logic. Works have been done on design and logic, based on the notion of imaginative constructivism (Hendriks and Kazakçi 2010; Kazakçi 2013); on design and models of independence like matroid (Le Masson et al. 2016a, b); on design and set theory, showing that there is a general design theory within set theory called forcing (Hatchuel and Weil 2007; Hatchuel et al. 2013b); and on design and category theory (Giesa et al. 2015, Breiner and Subrahmanian 2017). This led to novel results on generative functions (forcing, fractality…), to new approaches of system engineering (Kokshagina 2014), and to the notion of the interdisciplinary engineering knowledge genome (Reich and Shai 2012), etc.

In addition, a bootstrapping effect was demonstrated showing how independent knowledge structures from engineering and mathematics are brought together to allow the mutual generation in a cyclic manner of new concepts and theorems, and also new products such as foldable tensegrity structures (Reich et al. 2008).

Today advances in design theory open new spaces for research on design and machine learning, on design and deep neural networks, on design and novelty-driven algorithm, on design and new operation research, etc. Hence, design theory provides new foundations for constructive dialog with contemporary mathematics and logic.

#### *3.1.4 Stimulate new connections with social sciences*

The identification of the ontology of design provides the dimensions to direct the sociological, anthropological, organizational, epistemological and linguistic studies of design. These studies would contribute to understanding the conditions for generativity measured against splitting conditions and the social spaces at different levels. For example, these studies would help designing experiment with, and create new methods for, gaming, crowd sourcing, and open source models; they will help map the social to the splitting condition in the knowledge structures, to evaluating the generativity.

The PSI framework (Reich and Subrahmanian 2015, 2017) is an initial structure for enhancing these studies in a similar spirit to that of Elinor Ostrom's study of social structures and rules for governance of common pool resources (natural community resources forests, lakes, etc.) (Ostrom 1990). She has called for engineering approaches to studying economics and governance. Her work in developing a grammar for the design of these institutions is not very far from the theory of machines by Redtenbacher (Ostrom 2009). Building on Ostrom's works, some authors have proposed the notion of "common unknown" to extend the logic of common resources to design situations (Berthet 2013; Le Masson and Weil 2014). Exploring the dimensions of these parameters and their inter-relationship both empirically and computationally would allow us to predict the propensity for generativity across all species of design. Currently, these ideas are being explored in several projects with European industry to enhance participation of a larger set of independent knowledge to the design process through gaming and simulation. The goal is to explore both types of unknowns along all dimensions to enhance their generativity (Meijer et al. 2015).

It has been shown that the logic of the unknown and generativity is today at the heart of firm's strategy (Hatchuel et al. 2010) and organization (Hatchuel et al. 2006; Börjesson et al. 2014), as well as economic growth (Hatchuel and Le Masson 2006; Le Masson et al. 2010a). These studies have led to propose a theory of the firm based on firm's capacity to address the unknown collectively (Segrestin and Hatchuel 2008, 2011).

Hence, design theory appears today as a way to enrich the academic field of design by providing new foundations to discuss with design professions like art and industrial design, engineering design and scientists; it also enables connecting design researchers to mathematics and logic and social sciences; and it opens new theory-driven experimental protocols. But design theory is not only useful for scholars; it also contributes to the foundations for a renewal of the science and engineering paradigm in industry and in education.

### 3.2 Design theory to manage generativity in industry

To see how design theory contributes to the management of generativity in industry, we refer to the joint work with some of industrial sponsors. Based on the research results on design theory, they were able to invent new organizations, new methods and new processes (see also (Agogué and Kazakçi 2014; Hatchuel et al. 2015; Defour et al. 2010; Meijer et al. 2015; Reich and Subrahmanian 2015). This led them to get impressive industrial results—one illustration is given by the fact that some of them got also prizes like the RedDot award for their innovative products (Fig. 4).

The consequences of applying design theory in industrial organizations have been in the development of new organizational methods and processes for industry. A sample of examples shows how design theory contributed to change and improve the evaluation methods: the evaluation of innovative design projects (Elmquist and Le Masson 2009), and the evaluation and positioning of a portfolio of innovative design projects (Agogué et al. 2012; Le Masson et al. 2012b). How design theory has helped to position and improve existing design methods and processes are illustrated for example in ASIT (Reich et al. 2012), parameter analysis (Kroll et al. 2014), project management techniques (Lenfle 2012) and, CAD tools (Arrighi et al. 2015a, b). Design theory was also used to develop breakthrough methods for new innovative design processes. For example, KCP, a method, derived from C–K theory overcomes the limits of brainstorming or participative seminar in monitoring large groups in innovative design processes (Elmquist and Segrestin 2009; Hatchuel et al. 2009). More recently, new methods for patent design have been developed based on design theory (Felk et al. 2011; Kokshagina et al. 2014). Design theory provides a basis to characterize innovative design organizations in companies (Hatchuel et al. 2006, 2010; Le Masson et al. 2010b) or new collective forms of action like colleges (Le Masson et al. 2012a, b) and architects of the unknown (Agogué et al. 2013, 2017).

Another example of these developments is given by the work on serious games. Relying on design theory and the PSI framework, the authors were able to transform a serious game into a generative game, which enables to change the product (P), the social space (S) and the institutions (I) (Meijer et al. 2015; Agogué et al. 2015b).

## 4 Conclusion: design theory—enabling further research

As we have shown, in recent years, the body of work on design theory (and particularly the contributions of the design theory SIG community of the design society) has contributed to the reconstruction of a science of design, comparable in its structure, foundations and impact to decision theory, optimization or game theory in their time. These studies by reconstructing historical roots and the evolution of design theory have:

- unified the field at a high level of generality and uncovered theoretical foundations, in particular the logic of generativity,
- characterized "design-oriented" structures of knowledge following the splitting condition and
- identified the logic of design spaces in social spaces that go beyond the problem space complexity.

The results presented in this paper give the academic field of engineering design an ecology of scientific objects and models that have contributed a paradigmatic shift in the organization of R&D departments and innovation centers, in firms that have adopted the expanded design theoretical perspective.

The results presented further allow building advanced courses and education material [see for instance (Le Masson et al. 2017)]. They are being taught today in different countries (e.g., France, Sweden, US, UK, Israel, Tunisia, Japan) in various contexts: engineering schools, management schools, business schools, design curricula, entrepreneurship schools, and universities. The impact of these educational practices has been reported in several studies (Hatchuel et al. 2008; Dym et al. 2005; Hatchuel


**Fig. 4** Two reddot design awards won by industrial partners sponsoring research on design theory (Thales cockpit, reddot design award winner 2013; Renault Twizy, reddot design award best of the best 2012)

et al. 2011b; Nagel et al. 2016); Recent experiments based on a cognitive perspective have shown that theoretically grounded approach to teaching, significantly increases the capacity of students to resist fixation (Agogué and Cassotti 2012).

Emerging from the field of engineering design, developments in design theory has had a growing impact in many disciplines and academic communities. Design theory has and continues to have an impact in several academic fields, such as creativity research (Le Masson et al. 2011; Hatchuel et al. 2011b), data mining and knowledge management (Ondrus and Pigneur 2009; Poelmans et al. 2009; Goria 2010), history of engineering design (Le Masson et al. 2010a, b), psychology and cognition (Hatchuel et al. 2011a, b; Agogué et al. 2014), ecology (Berthet et al. 2012), philosophy (Schmid and Hatchuel 2014), and economics (Colasse and Nakhla 2011). For the design community, design theory can be a vehicle for interaction with other communities, such as design computing and cognition (DCC), the European Academy of Design (plenary conference on Design Theory by Armand Hatchuel in 2015), the Euram Academy of Management (that includes a full track on design paradigm in management since 3 years), International Product Development Management Conference and R&D Management Conference that welcome papers based on design theory, Project Management Institute, and the International Council on Systems Engineering.

Design theory also opens new collaborations beyond research done with engineers and industrial designers. Recent collaborative research with entrepreneurs and entrepreneurship programs such as the Chalmers School of Entrepreneurship (Agogué et al. 2015c) is illustrative. Further collaborations are being pursued with scientists and designers of scientific instruments (collaboration on Herschel experiment, with INRA, with CERN, with the Center of Data Science, with the National Institute of Standards and Technologies (NIST).

The claims we make in this paper are strong. As a culmination of work over close to 10 years of SIG existence that rests on many years before, by many people from diverse disciplines. We feel the claims are warranted. Furthermore, strong claims make it easy for other researchers to test them or object to them by conducting experiments or developing new theories. True progress requires clear claims that could be challenged. We invite design researchers to do precisely this.[11]

In asking researchers to challenge our claims, we acknowledge that there are limitations to our results. For example, with respect to forcing; there are open issues on forcing in mathematics and we do not claim it is the only way to be generative. We do not claim any special status of any of the theories mentioned in this research summary. We do not even claim special status about the ontology of design. Rather, it is a synthesis of theoretical and empirical work that led to its evolution over the 10 years of the SIG's existence and it may continue to evolve in the future.

The design community may play a significant role in addressing contemporary challenges if it brings the insights and applicability of design theory to open new ways of thinking in the developing and developed world. And of course, in this effort to develop design theory for the community, one can keep in mind the basic questions coming from design theory to characterize a "design oriented" community such as the design society and the design theory SIG of the design society: are we generative? Where is independence in our knowledge structures? Are we an open space?

**Acknowledgements** We thank the reviewers of this paper for their useful comments that have helped making the paper better. The design theory SIG acknowledges the support of the design society and the industrial sponsors. We also thank all the participants in the workshops over the last 10 years.

[11] In this invitation, we are being consistent with our proposed ontology of design, adhering to the principle of reflexive practice (Reich 2017). Developing better design theories can arise from diverse independent knowledge that may come from opening the social space of people involved in the generation of new theories.

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## Kilian Gericke

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He is interested in the effects of new concepts such as Product Service Systems (PSS), Cyber Physical Systems, and of new manufacturing technologies such as Additive Manufacturing (3D printing) on the design process and in the development of new design methods that support designers in this context.
He is co-editor of the book “Pahl/Beitz Engineering Design” and co-author of the revised VDI 2221 guideline. Prof. Gericke is elected member of the Advisory Board of the Design Society and is chair of the Design Society's Design Process Special Interest Group.

**Title of the Presentation:**
An overview on the Design Methodology by Gerhard Pahl and Wolfgang Beitz

**Synopsis:**

Presentation of the genesis and of the main content of the Pahl/Beitz method, its influence on German design research and its relation to VDI guidelines (VDI = Verein Deutscher Ingenieure, German Association of Engineers). Starting from the revised edition of Pahl/Beitz and VDI2221 ongoing and future research topics will be discussed.

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Design Science

# Supporting designers: moving from method menagerie to method ecosystem

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## Abstract

Supporting designers is one of the main motivations for design research. However, there is an ongoing debate about the ability of design research to transfer its results, which are often provided in form of design methods, into practice. This article takes the position that the transfer of design methods alone is not an appropriate indicator for assessing the impact of design research by discussing alternative pathways for impacting design practice. Impact is created by different means – first of all through the students that are trained based on the research results including design methods and tools and by the systematic way of thinking they acquired that comes along with being involved with research in this area. Despite having a considerable impact on practice, this article takes the position that the transfer of methods can be improved by moving from cultivating method menageries to facilitating the evolution of method ecosystems. It explains what is understood by a method ecosystem and discusses implications for developing future design methods and for improving existing methods. This paper takes the position that efforts on improving and maturing existing design methods should be raised to satisfy the needs of designers and to truly support them.

**Key words:** design method, design methodology, design research, validation, transfer

**Received** 03 July 2019
**Revised** 04 August 2020
**Accepted** 05 August 2020

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*Des. Sci.*, vol. 6, e21
journals.cambridge.org/dsj
**DOI:** 10.1017/dsj.2020.21

## 1. Introduction

One of the stated purposes of design research is to provide support for industry for designing better products in a more effective and efficient way, for example, by studying designers, teams, organizations, or users as well as technologies, products or systems (Horvath 2004; Blessing & Chakrabarti 2009; Tomiyama *et al.* 2009; Reich 2010; Andreasen 2011; Braha *et al.* 2013; Cross 2018).

While there are many examples of such support in form of methods, tools, guidelines or processes that has had a direct and significant impact on individual companies, it has proven to be more challenging to evidence the contribution of design methods and other types of design support to industry at large (Daalhuizen 2014; Jagtap *et al.* 2014; Gericke, Kramer & Roschuni 2016; Cross 2018).

Much research on methods has not yet had a lasting effect on the wider industry (Wallace 2011). One of the vehicles of affecting industry beyond a specific collaboration with partners is through the development of methods that industry can follow. Industry does work undeniably in a systematic way (Daalhuizen 2014), but more evidence is required to show that they follow methods proposed by the academic engineering design research community (Tomiyama *et al.* 2009). Once companies have adopted a method, they often use it for a long time, but sometimes for purposes that it is not intended for (Gericke *et al.* 2016).

This position paper argues that one of the roots of the problem is that universities develop a plethora of methods in isolation, rather than offering industry methods and tools that they can adopt and adapt to their context and fit into their existing set of methods.

Universities and businesses have different goals and operate at different time scales. Universities traditionally aim to excel through rigorous research, which contributes to knowledge and are tied into academic funding and degree cycles, whereas businesses aim for productivity to assure a profit through the timely delivery of high-quality products. However, academia is increasingly assessed through the impact of their research on business (primarily) or society. Therefore, the question of how method development can make a contribution to industry is becoming more pertinent.

The title of the paper alludes to the current state of method development through academic engineering design research. This development is akin to the menageries before modern zoo keeping was developed. Exotic animals like lions or rhinoceroses were kept in unsuitable cages and displayed to the royal visitors or the general public. Many methods are similarly displayed at conferences or in publications and forgotten soon afterwards. Instead, what we should aim for is an ecosystem of methods that coevolves in an impactful way within the industrial application environment. Some methodologies that have been developed over the years (such as Pugh 1991; Roozenburg & Eekels 1995; French 1999; Andreasen & Hein 2000; Frey & Dym 2006; Pahl *et al.* 2007; Cross 2008; Ullman 2010; Vajna 2014 and others) describe a consistent set of methods and thus could be considered as an ecosystem. It should be noted that the term design methodology is differently used within the design research community. Roozenburg & Eekels (1995) discuss the differences. The main difference is between understanding design methodology as 'the study of methods used in a particular discipline' compared to understanding used here (compare Table 1) – 'a specification of an overarching approach to producing an artefact that specifies what the different activities are, what methods should be used to perform them, how to sequence them, what their information outputs should be, and (frequently) how to describe the information produced at each stage' (Gericke, Eckert & Stacey 2017). However, design methodologies assume an idealized environment suitable to support design education, but do not (and cannot) describe the large variety of industrial contexts. These works represent artificial ecosystems. In this paper, a method ecosystem is understood as a set of methods that can coexist in a self-sustaining way. We distinguish between such ecosystems that can be found in practice, which often evolved over time

**Table 1.** Examples of different types of design support from Gericke *et al.* (2017)

| Term | Explanation |
|---|---|
| Design methodology | In design, a clearly and explicitly articulated approach to producing designs for a class of systems, that specifies in more or less detail the activities to be carried out, the relationship and sequencing of the activities, the methods to be used for particular activities, the information artefacts to be produced by the activities and used as inputs to other activities, and how the process is to be managed, as well as (tacitly or explicitly) the paradigm for thinking about the design problem and the priorities given to particular decisions or aspects of the design or ways of thinking about the design. |
| Design process | In design, (1) A formally specified sequence of activities to be carried out in developing a particular design, or a class of designs, which will often be an application or customization of a methodology to a particular problem. (2) The actual sequence of activities carried out in the development of a design, which may correspond more or less well to any formally specified process. |
| Design method | A specification of how a specified result is to be achieved. This may include specifications of how information is to be shown, what information is to be used as input to the method, what tools are to be used, what actions are to be performed and how, and how a task should be decomposed and how actions should be sequenced. |
| Design guideline | In design, a statement of what to do when, or what should be the case under particular circumstances. One should only be violated for a good reason, with a careful consideration of the consequences. |
| Design standards | In mature areas of design, standards are a binding set of prescriptive steps that need to be followed and – unlike guidelines – can be audited. |
| Tool | An object, artefact or software that is used to perform some action (e.g., to produce new design information). Tools might be based on particular methods, guidelines, processes or approaches or can be generic environments that can be used in conjunction with many methods. |

and ecosystems that are used primarily for teaching. We refer to the latter ones as artificial ecosystems. Some are based on observation of good practice (i.e., descriptive approaches) while others are prescriptive and provide usually generalized guidance for designers and students (Blessing 1996; Gericke & Blessing 2011, 2012; Gericke, Qureshi & Blessing 2013; Wynn & Clarkson 2018). As a conclusion, all design methodologies are ecosystems but not all ecosystems are necessarily design methodologies.

This critique does not want to diminish the usefulness of these works but aims to motivate the further development of the field of design research.

Design methods are embedded in a complex environment. They influence and are influenced, for example, by the task, the design process, the individual prerequisites of the designer, prerequisites of the group and external conditions (Frankenberger & Badke-Schaub 1998). The integration of methods into the process is twofold, into the sequence of tasks in which they are used and with each other. This implies a common vocabulary or at least an explicit vocabulary, which allows a translation and models that can be linked up. The need for the integration, or at least the possibility of integration, of methods might be greater than ever

before, as products are becoming more complex and interdisciplinary, companies aim to deliver holistic user experiences based on new business models and the development processes are becoming more global (Nguyen, Müller & Stark 2013; Kimita *et al.* 2015; Eckert *et al.* 2019; Wichmann, Eisenbart & Gericke 2019). For example, Industry 4.0 will require a greater integration between software, hardware and electronics. Sensors on the product and its production lines as well as more powerful simulations will generate unprecedented volumes of data. Principles of circularity and sustainability will become commercial and moral imperative (Tukker 2015; Man & Strandhagen 2017; Cong, Zhao & Sutherland 2019; Wichmann *et al.* 2019). All this requires greater transparency in the ways of working and greater collaboration with other fields; and therefore, engagement with their tools and methods and ideally a coordination across different disciplines to assure that gaps and incompatibilities do not cause inefficiencies and product failures. Hence, the design research community needs to be ready to engage and gain an understanding of how to support industry through methods that are fit for the evolving industrial practice. The current problems and future challenges raise the question whether the gap between engineering design practice and engineering design research is actually increasing rather than narrowing at a time when the integration of disciplines in products require coherence within disciplines, that is, the disciplines can collaborate in a logical and consistent way using mutually understood concepts and representations. We therefore postulate that the community needs to urgently step up its efforts.

Many design methods are developed as part of PhDs or time-limited research projects. As such, they play an import role in training the next generation of engineering design academics and industry experts (National Academy of Engineering 2004; Eder 2007; Blessing & Chakrabarti 2009; Tomiyama *et al.* 2009; Cross 2018). Publications on methods play an important part in building our community through discussion at conferences and in journals. When time and funding runs out, many of these methods or tools are not developed to a point, where they can be picked up by industry or other academics (Gericke, Meißner & Paetzold 2013). Industry can benefit greatly from being part of these research efforts and from hiring people with expertise in methods.

However, for our research community to have a greater impact in industry, we argue that we need to create systems of usable methods that engineering designers in industry can use. This does not imply that all methods need to be connected or that the research community needs to reach a consensus on one common way of looking at design research. Rather the paper argues that methods need to be developed to a sufficient degree that industry can use them in conjunction with existing methods without the creators of the methods being actively involved; and that academic publications explicitly discuss how proposed methods can be used in conjunction with other methods. We should strive to improve and extend existing methods to give industry continuity, rather than researchers addressing limitations by starting from scratch to develop a 'new' method. Similar arguments apply to the need to create joint up and compatible tools, however this paper will focus on methods.

This position paper is a collective effort by members of the Design Process Special Interest Group (formerly known as Modelling and Management of Engineering Processes – MMEP) of the Design Society. It has arisen from a series of workshops at the International Design Conference DESIGN'16 (>30 participants) and DESIGN'18 (>40 participants) as well as two specially convened workshops in October 2016 (15 participants) and in November 2018 (12 participants).

The authors of this position paper represent a diverse community – representing different nationalities (Germany, UK, Canada, Sweden, Italy, Greece), different communities (Design Society and ASME with backgrounds in Engineering Design, Systems Engineering, Design Optimization, Computational Design, Design Theory) and different career paths (one currently in industry, four with industrial background and currently in academia and six in academia). Most of the authors are serving as editors or reviewers for leading academic journals, conferences and funding bodies. All the authors have been engaged in developing methods for up to 25 years and have had both successes and failures in introducing their own methods into industry and have had numerous discussions with industry experts on the barriers of introduction. From this experience, the paper is making claims about the challenges of introducing methods in industry, that have resonated with all the authors.

The authors developed the position of this paper together starting with 2 days of discussions at the workshop in November 2018. The main insights were summarized in this paper, which was improved through several rounds of comments and rewriting. This position paper is not a review paper. As a position paper, it is intended to stimulate discussions about the addressed topic, related challenges and of course about the position presented here.

## 2. Design methods

### 2.1. What is a method anyway

Building on Blessing & Chakrabarti (2009), Gericke *et al.* (2017) set out to clarify some of the central concepts of design research (see Table 1) with which the term method is often mixed up.

A design methodology is an approach that combines methods, guidelines and tools, each of which can exist individually, according to a process that organizes design activities, and the use of the methods and tools. The application of methods and guidelines, and the organization and performance of the process, can be aided or enabled by the use of tools.

A method has multiple elements, which comprise the core idea of the method, representations in which design information is described, and a procedure. Core idea, representation and procedure build on each other (see Figure 1) and form the method, thus the method description should provide the necessary information about each element of the method as well as information about any tool implementation of the method if available or required. A method might have dedicated tools, shared tools with other methods or use generic tools (see Gericke *et al.* 2017).

The method description should provide, besides explanations of each element of the method, information about possible adaptations of representations and procedures that allow the method's use in different contexts, as well as information about the required rigour in the application of the method. Some elements of a method might allow adaptation while other elements, for example, those required for or related to compliance, should not be modified. For example, the same method could use alternative representations, such as using graphs instead of matrices. Method users should be informed about such options and limits of adaptation.

Dorst (2008) has criticized engineering research for concentrating on the activities required to carry out a task and therefore focusing on efficiency and

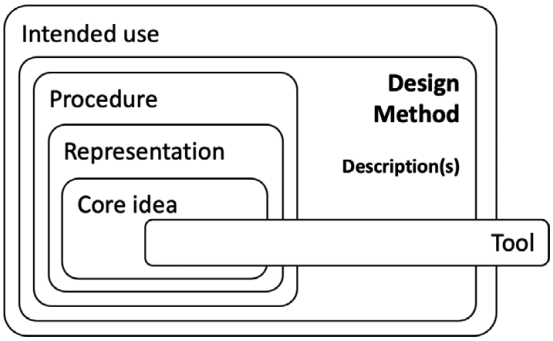


**Figure 1.** Elements of a method from Gericke *et al.* (2017).

effectiveness, while neglecting the object, the actor and the context in which these activities are carried out, however we see these an integral part of design methods where the actor is considered in the procedure and the context and the product in the intended use.

## 2.2. Current impact and relevance of methods in industry

The development of new means that support designers in their work (e.g., methods, tools, guidelines, processes and methodologies) is central to engineering design research (Blessing & Chakrabarti 2009). Analyses of method uptake by industry create a contradictory picture. While it is repeatedly stated that industry does not seem to use design methods (Araujo *et al.* 1996; Birkhofer *et al.* 2002; Geis *et al.* 2008; Tomiyama *et al.* 2009; Jagtap *et al.* 2014), many companies claim that design methods are central to their activities and enable them to be innovators in their field (Maylor 2001; Design Council 2007; Booker 2012) as evidenced by the many publications by industry experts in conferences and by the activities of professional bodies.

The validation of design methods in relation to the industrial context of deployment is problematic at best. Engineering design researchers refer to the Validation Square (Pedersen *et al.* 2000) as a reference framework for the validation process of design methods. The strength of this framework is that the evaluation establishes both efficiency and effectiveness of the design methods, by considering both theoretical and empirical validity criteria. Within the context of this framework, the fundamental limitation faced by academic engineering design researchers is with the 'external validation', that is, the reproducibility of the validation experiments results within the users' environment, proving the utility when industrialists deploy the design methods. This invariably limits or delays the take-up of the design methods in industry, where in the face of commercial pressures proven methods are commonly preferred.

Assessing the dissemination and uptake of design methods is difficult, as companies may use methods in a modified form and may use different names for the methods they use (López-Mesa & Bylund 2010). Gericke *et al.* (2016) report that many of the practitioners interviewed for their study did not know the academic names of methods they use and many were not aware that they were working in a structured manner and were in fact applying a version of an existing

method that they had come across in the past. Engineering design processes include methods, but there can be a complicated relationship between the methods actually used and the published versions of the methods and to designers' perceptions of the methods.

However, measuring the impact of an academic research goes beyond an assessment of the direct uptake of its research results. Design researchers are domain experts that influence design practice by proposing, by knowing, and by teaching. Design research results are often based on analyses of practices and design problems of industry, thus provide analyses and propose good practices that have been shown to be successful. Research results influence the education of the next generation of experts as well as it influenced current and past generations. In this way, many of the underlying concepts of design methods and methodologies indirectly influence design practice (Eckert & Clarkson 2005; Cross 2018), even though this influence is slow and hardly traceable and measurable.

This research community impacts design practice by the direct transfer and uptake of research results, as well as through the highly qualified engineers (BSc, MSc and PhD) they train. Over the last decades design practice has undergone tremendous changes and many of these changes were enabled by research results, driven by research results or built on research results. For example, Quality Function Deployment (QFD), SixSigma, Failure Mode and Effects Analysis (FMEA) and many of the CAD tools started in early engineering design research (Hein 1994; Cross 2018).

While the assessment of the impact should not be reduced to a single measure – the uptake of methods, tools etc. by industry – it certainly is an important channel that deserves continuous reflection, improvement and adoption to new trends and needs.

## 2.3. Key challenges for improving the uptake of methods

The development of methods that industry can use is fraught with difficulties on multiple levels arising from both the way academia and industry work and from the way the two groups interact with each other.

A significant part of the research community lacks awareness of the plurality of methods and the implications for both the industrial application of our collective research and our academic credibility. The consequences of this phenomenon have been discussed for research around function modelling, where a multitude of internally consistent notions and resulting methods have been proposed but hampered their uptake because of their coexistence. Vermaas & Eckert (2013) state the problem clearly: 'The coexistence of these different traditions is now hampering further developments and usages of functional description in academia and industry. At conferences, new results and applications of functional descriptions are presented, creating progress within the separate traditions but limiting opportunities for cross-fertilizations. In the dissemination of results to industry, academia effectively exports its separation in traditions, thus arriving at the less attractive proposition that industry should adopt the different ways of giving functional description and implement methods and tools that are not straightforwardly combinable'.

Methods for industry need to be built on a strong understanding of industrial practice; but this is not enough, we also need evidence that support our claims of

improvement, that is, examples and evaluations that are based on problems that truly match challenges in industry, which go beyond the typically used toy problems. Managers in industry want to see real industrial examples and see measure of increased efficiency.

#### 2.3.1. Causality

Claims behind the success and failure of methods in industry are assuming that there is a causal connection between the method and the results that arise from it. However, arguing causality is problematic for the following reasons:

**Multicausality:** No two design problems are the same and all design processes are subject to multiple constraints and characteristics that affect them. The success or failure of both products and processes can be due to many factors. This makes it difficult to attribute any improvements directly to the methods that are used. If the new generation of a product was designed faster using a new method, than the last generation, this might be due to the method, but it could also arise from a different amount of required change or different people. Conversely, a project might struggle in spite of good methods, because it is running in unexpected problems such as cliff edge effects in the product. An inappropriately chosen or used method can also have a negative impact on quality or lead time.

**Hawthorne effect:** The Hawthorne effect was originally discovered in the 1930s when a team of researchers attempted to change the working conditions in a factory. When they change the set up back to its original state after multiple modifications while achieving continued efficiency gains, they realized that the improvements they achieved were not due to the change they made, but the attention they have paid to the factory, the process and its workers.

**Notions of causality:** In evaluating methods, we need to create a causal connection between the methods and the effect it has for industry. This raises the question: what an appropriate notion of causality would be for methods? A typical notion would be counterfactuals (ref), that is, if A leads to B, then not A would also lead to not B. While this is appropriate in the context of risk and failure, it is unlikely to be possible to prove, that without a method a product would not have been successful. Therefore, it might be more appropriate to think of a causal push, that is, A makes B more likely. Translated to methods, this means that applying a method makes it more likely that something is achieved. However, if the method is associated with an improvement it is it difficult to prove that this can be attributed to the method. If no improvement occurs, it does not mean the method has failed, as other factors could affect the measure.

#### 2.3.2. Academia

The way design research is operating under the pressure of academia also contributes to the challenges of introducing methods into industry. To a certain extend this might be a matter of perception as many publications claim that methods have been developed, before they have been successfully applied or tested in an industrial context (see, e.g., Pedersen *et al.* 2000 for the discussion on how to validate methods).

**Lack of theory:** In spite of isolated efforts, design research still does not have comprehensive theoretical underpinnings that enable us to predict how design processes behave, given the nature of the product being designed and the way the

organization and the design process are configured. This deprives us of a theoretical means to assess the scope of methods and to support the generalization of processes or best practice into generally applicable methods.

**Premature publishing:** The publish-or-perish culture of academia pushes our community publishing of methods before they have been properly developed. A publication it is often the promise of a usable method, when in fact it only expresses the core idea of the method, maybe with an application example rather than a fully developed and evaluated method. Many ideas for methods are developed as part of doctoral theses. As an individual student can rarely develop and evaluate a method in its entirety methods are often published in a prematurely stage. If this student moves on to industry or loses the opportunity or interest to develop the method further, it never matures. However, publishing methods that are under development is an essential part of academic discourse.

**Knowledge islands:** Methods and entire approaches to engineering are often developed in response to the specific challenges the collaborating companies are facing, or in response to specific and narrow new technology development. This has contributed to different research groups or cluster of research groups having developed their own approach, view and terminology around design as the plethora of definitions and methods for functional modelling illustrates (Eisenbart, Gericke & Blessing 2013; Vermaas 2013). This would not be a problem, if work would build on each other or clearly articulate the differences. Attempts to compare and benchmark different methods and approaches against each other is still in its infancy. A special issue on benchmarking functional modelling illustrated that most authors thought of benchmarking more in terms of increased citation than a deeper comparison, which the editor still welcomed (Bohm *et al.* 2017) rather than an analysis of the strengths and weaknesses of their method compared to others.

**Disciplinary silos:** Academic research on methods for engineering design and product development still happens in narrow disciplinary boundaries and cross disciplinary collaboration occurs rarely even though for example the computer science, operations research and the technology management community work on related issues and use similar methods with different names. To create ecosystems of methods researchers from different fields need to come together around a shared understanding of the industrial context and its needs.

**Lack of focus on validation**: Much of design research in academia tends to focus on development or refinement of new methods with an emphasis on theoretical structural aspects, rather than the empirical validation of the methods in a real engineering and industrial context. This is also a reflection of the historic self-centric attitude in academic publishing of engineering design research, in that higher value tends to be attributed to rigorous papers that present an innovation or structural enhancement of a method, rather than empirical deployment enhancement studies, positioned in an external industrial context and focused on the social aspects of method enhancement and deployment.

#### *2.3.3. Understanding of industrial practice*

Academia and industry collaborate in many different ways. Individual researchers or research groups have often found their own ways of working with partner companies from case studies, student projects and funded projects to consultancy

or exchange of stuff. However, the number of companies each individual or group can work with is limited and direct comparisons between competing companies is often infeasible or unethical. Nevertheless, there are some common issues around generating and sharing knowledge about industrial practise.

**Publishing descriptions of practice:** Engineering design is usually carried out in large teams. The development of highly complex products, such as aircraft involve 10,000s of people across the supply chain as does the development of the systems of systems. This makes it impossible for any individual or group to fully understand the challenges the product development processes face and the product development contexts in their entirety. However, even applied to narrow areas, few researchers understand industrial practice in particular beyond individual companies. Sharing understanding from practice can be difficult since publishing purely descriptive papers can be a challenge as reviewers demand methods or multiple case studies. Conversely industry papers that report on developments of methods or implementation of the methods are often considered less rigorous and difficult to publish.

**Understanding differences between practitioners:** Localized work culture plays a huge role in success and failure of methods. Companies are organized in different ways and often reorganize their structure and management. This can render insights outdated or irrelevant. Individual teams are motivated in different ways and respond to the introduction of a method based on past experiences. The time of method introduction can be critical since teams are very receptive, if the method addresses a problem they are currently faced with.

**Academics from industry:** Some academics have been working in industry before joining academia. This can be an enormous advantage provided the academics also have the methodological training and experience to conduct rigorous research; however, it can also be a source of bias. Even with an industrial background it is important that academics get exposure to multiple companies and sectors in particular, if they have spent their entire professional live in one company. The balance between academics with industry or academic backgrounds vary enormously between countries, which has generated research subcultures with slightly divergent objectives.

**Funding for industry research:** Government funding councils tend to be highly directive and tend to look for innovative research and often new technology. It can be a challenge to get method research funding in particular up to a level when methods would be fully described and validated. Many research groups obtain funding directly from industry. However, in this case the funders' interests lie in addressing their own problems, rather than assuring a general applicability of methods, even if the results are presented to the academic community in those terms.

**Trust between industry and academia:** Method development requires sustained funding and long-term commitment by both industry and academia. This requires long-term personal relationships and an understanding by both parties that on route to robust methods and tools the collaboration will bring benefits for both parties, such as feedback on existing processes or activities in the companies by academics as part of their research. The necessity of personal relationships creates uncertainty for said long-term collaboration, in that the consequences of key stakeholders leaving might endanger such cooperation. As such, formalization efforts of collaboration might be one way to go, for example, establishing industry-academia research councils which manages and sustains such collaborations.

## 3. From isolated methods to a method ecosystem

This paper takes the position that instead of proposing isolated invalidated methods that are insufficiently evaluated for a wide-range of applications we need to reach a point where methods are robust, have a clearly defined scope and are embedded in an ecosystem of methods, that is, a set of methods that can coexist in a self-sustaining way.

Originally the term ecosystem was applied to 'a biological system composed of all the organisms found in a particular physical environment, interacting with each other; in extended use: a complex system resembling this' (Oxforddictionaries 2017). Over the past three decades, the term has been used for the increasingly complex integration of organizations, humans, materials and information flows across the product lifecycles. Based on a comprehensive review of literature, Tsujimoto *et al.* (2018) have defined the objective of the ecosystem in the field of management of technology and innovation as 'To provide a product/service system, a historically self-organized or managerially designed multilayer social network consists of actors that have different attributes, decision principles, and beliefs'. In this sense, every product development process can be thought of as an ecosystem of its own. However, for the purpose of this paper, we think of methods and the tools that support them as an ecosystem.

### 3.1. 'Paradise' scenario

Before describing what best practice on method development could be, let us look what an ideal state of methods would be. To provide another analogy let us think of methods as tools in a builder's toolbox. Novices have to learn to use the tools. When they are asked to cut a stone to a particular shape, they have to select the right tool and then focus their attention on how to use the tool to do tricky tasks, such as cutting out neat corners. Master builders understand and master their tools. They know where and in what situation to deploy a particular tool. They understand the sequence of the activities that need to be carried out and therefore knows when which tool needs to be available. Master builders are not focussed on the use of tool but concentrate on what they are building. The master can concentrate for example on the shape they are generating and what angle the corner should have. A master can generate the shape they want, not the shape they can create given their understanding of the tools. The reflection in action is a well-recognized aspect of design (Schön 1983). However, the reflection should be mainly on the object that is being designed, rather than on the designer's ability to use the tools by which the work is being generated.

The master builder has some specialist tools, which enable him to carry out a specific recurring task very efficiently, such as moulds for particular shapes and general tools, where they need to think how the tools are applied to a given task. Master builders have a differentiated understanding which tool is appropriate.

The ideal scenario of methods would be an equally smooth interaction with multiple targeted methods so that the designers can really focus on what they are designing. The designers would also select their methods with ease and rely on the methods to deliver what they need. As a multitude of methods is used during the development process, these would fit together so that no time and effort is lost is divergent vocabularies and logics of modelling. The designers would also adopt

new or enhanced methods to avoid crisis from developing. Design methods should not become invisible and should not require zero mental effort. Design methods should not make the work more complicated. A method can require attention and can require even substantial mental effort; however, they should not increase the effort and not distract from the work that needs to be done.

In short, in paradise, methods are unobtrusive and dynamic in the same way as to that of a pen lying on a notepad during a meeting. Invaluable and invisible, with only its absence marking its importance.

Like the master builders the engineering designers would have invested time and effort into learning their methods and deploy them on multiple projects so that they can be masters. At the same time, they would be open to invest time to adopting and integrating improved and new methods provided these offer a clearly perceived benefit. Academics would understand the needs of industry and direct their efforts to newly arising challenges and desires of industry. In dialogue and sympathy, they would develop new methods before their lack becomes a real issue, for example, the tools and methods to make best use of new technology would be in place.

### 3.2. We must be able to measure impact of methods

If we want industry to take up the methods developed by our community, we need to give them the confidence that the methods are ready to be deployed and add value to their operations. There we must be able to measure the effects that are claimed, such as effectiveness and efficiency or the time it takes to master the methods. This implies that it is necessary to clearly state the expected effects.

While there are theoretical challenges to measuring the effectiveness of methods, there are pragmatic actions we can take in order to assess methods, such as interviewing the participants, running evaluation questionnaires or doing a detailed comparison with other projects.

Like with products, changes and adaptation might be necessary once the method is actually used. Some companies already employ teams to select and monitor methods – 'governance' of processes and methods. However, if these teams are outside of the departments, they might be too distant from the actual process to assess it as they can neither observe the process or access the process data; and they might be ignored or resented by the practitioners. As a community, we need to work with these people and bring them into our community so that we can all build on their experiences. This has for example been accomplished successfully by the DSM community, that runs annual conferences with high industry participation.

The expected effects of using design methods can vary from being more efficient to being more creative or simply being able to achieve something that is usually too complicated or too complex to attempt, thus being more effective. An important part of effectiveness is also to have teams enjoy the work that they are doing more and freeing them up to be more creative and innovative. This indirect link between systematic design methods and innovation is often overlooked. Many methods are of course directly targeting creativity.

A system of measuring the effectiveness of methods carries risks for the designers who are using the methods and the research who generate them. As in other walks of live any measure carries with it the risk of being gamed. Instead of

working towards the ultimate goal, the entities work towards maximizing their scores. Measuring also carries with it the risk of the Hawthorn effect. Measuring the effects of a method is fundamentally measuring the performance of the people which needs to be handled with care.

A change of culture in organizations is required to overcome some of these challenges. The introduction of methods needs to embrace the organization and communicate the rationale for methods. Rather than giving employees the feeling that they are measured, the results created through the method could be assessed and designers could become incentivized to improve and adapt methods.

At the same time, we need to be able as academics to evaluate the effect that methods are having in practice. While related to the performance measures industry would use, the academic criteria of improvement could be wider or more qualitative.

### 3.3. Research of practice and practicing informs the development of methods

The applicability of the design methods depends on the intended context. As part of the development of methods, we therefore need to aim to understand this context. It is of course not practically possible for researchers to try out a method in a large number of different context (Gericke *et al.* 2013).

The first step has to be to avoid overclaiming the area of application of methods. In research publications, we need to honestly report in which context a method has been deployed: what was the product? Was the method used in a real environment? What simplifying assumptions have been used? Many methods developed by researchers have been used only on a toy problem. What works for a mouse trap might not scale up to a helicopter. However, what we can do is to characterize the properties of the application case as accurately as possible and reflect over how these characteristics of the problem or organizational context have affected the success of the method. For example, a method that depends on a product Design Structure Matrix (DSM) in early stages of the product development process, like Change Prediction Method (CPM) (Clarkson, Simons & Eckert 2004), can work in the context of mature and incremental products. It also only provides benefit for products of a certain complexity, too simple and the method has little benefit, too complex and the product breakdown is either so abstract that vital characteristics are lost or so large that it is difficult to read the matrix.

Only an understanding of practice allows researchers to anticipate at which practical problems users of the method are likely to trip up. For example, an unsuitable visualization can make it very difficult for people to read dependencies. To return to the example of change prediction, a matrix is an excellent and complex way of seeing dependencies, but graphs are much better at seeing paths (Keller, Eckert & Clarkson 2006). The onus of making methods useable in different applications and contexts should lie with the developers of the method.

Practitioners also often abandon methods when they run into small problems that are time consuming to resolve. Therefore, they need guidance on how to deal with these issues. For example, one of the challenging issues when generating change propagation matrices are small components in the product breakdown, that have been overlooked in the past. If methods are presented with carefully described examples on which it has been validated, the implication of the scope of

the method can to some extent be left to the imagination of the reader whether they can apply the method in their own context.

The need for a detailed understanding of the context raises the question how this can be instilled in the researchers who develop methods, who are often graduate students. Few books exist that describe engineering design practice (which notable exceptions of sociologically oriented books, e.g., Bucciarelli 1994; Henderson 1999). Therefore, the burden to give students exposure to industrial practice through joint projects or placement lies on the universities and industry collectively. In particular, researchers need to learn and reflect how companies use methods and how the methods are introduced into organizations in order to be able to deploy methods that can be applied themselves. Introducing new methods is a cascading process drawing on complementary skills. Of course, we cannot assume that all researchers have equal access to companies or have equal skills to work with organizations. Therefore, we need to generate an environment where people with different skills and inclinations work together on methods within groups or across universities. For example, in the development of CPM the empirical studies were done by engineers and the algorithms were largely coded by a mathematician who also joint into the empirical studies. The choice of the tools and methods is not always up to an individual organization but might already be prescribed by guidelines or standards which companies might choose or have to adopt to.

### 3.4. Ecosystem of methods

In this paper an ecosystem of methods is understood as a system of methods embedded in an organization, where methods operate in conjunction and where users implicitly understand how methods can be adapted and how they are connected to each other. This requires a degree of communality in the terminologies used as well as a clear articulation of the input and outputs of methods. Like in an ecosystem each method has its distinct characteristics and purpose, but the methods also overlap in scope and to a certain extend compete with each other. An ecosystem is not a fixed set of methods, but a system in which methods can be added if a need for them arises and multiple methods can fulfil similar roles. An ecosystem does not lead to a stringent recipe of how to proceed but provides and suitable methods and a structure in which the methods can be used. The same goal can be achieved in multiple ways, that is, through different combinations of methods, adaptations of methods and by a flexible/opportunistic choice of when to use a method or not (Bender & Blessing 2004). This choice is important to enable users to tailor their processes to the products and means of production they are addressing and also give them a sense of control over their processes. An ecosystem is therefore far richer and more flexible then a design methodology, which ties a set of methods together in a suggested structure. It provides numerous of methods for different purposes and ways to combine and supplement them.

Methods need to reach a certain degree of maturity over time, which might necessitate research on maturing and improving existing methods. This needs to be recognized as research in its own right and funding must be provided. Method development is not a game of method innovation, but of method maturation. In the context of academic research method improvements therefore need to be articulated and acknowledged as contributions.

As in natural ecosystems there is not only a single ecosystem of methods, but multiple clusters of researchers or communities of practice have their own ecosystems, for example as they belong to the same industry sector, nation or lead academic discipline. There might be some methods that are common in all or at least many different ecosystems, while other methods are highly specialized. The ability to combine is important as companies have their own in-house methods, that they want to combine with methods developed by the research community. Which method ecosystem is the right one and into which a new method is to some extend a matter of choice, but also a matter of suitability as some methods are developed specifically for a particular application.

Ecosystems are open, as researchers and industry experts move between companies. They evolve. At the same time an ecosystem also implies a degree of stability as people become familiar with methods and learn how to deploy methods. Just as animals learn to adapt to their ecosystems, methods also need to be given the chance to evolve to find their own niche in an ecosystem.

### 3.5. Ecosystem of the research

To achieve an ecosystem of methods we also need to generate a community of practice of researchers and practitioners, this will become even more important in the future as product development processes become more interdisciplinary and therefore the need for cross-disciplinary methods increases. We need to foster the collaboration across research groups, across disciplines and across noncompeting companies so that they can learn from each other (Gericke, Qureshi & Blessing 2013). As academics, we often have the privilege to work with a variety of different companies. As we train them in the use of the methods that we develop we might also be able to bring them together and enable them to exchange ideas and practices of the methods. This exchange is also an opportunity for us to learn how our methods can become more robust and applicable. Ultimately the onus is on us as researchers to create and foster communities of practice around the methods we are generating. Different communities of practice can also learn from each other, so that we build up the knowledge how to create and apply methods more efficiently.

The development of tools and methods requires a range of different skills and involves many different activities from understanding the industry contexts and developing the steps of the methods to the underlying theory development. Elements of method development might involve a different mix of academic disciplines to those that the companies use in deploying the methods. In understanding practice and developing methods we might need to work with natural and social scientists from different fields such as psychologists or sociologists. However, it might be difficult up front to anticipate which disciplines this might be before we have engaged in detail in the process.

It is important to communicate this to the funders who want in depth explanation as well as detailed ethics plans before we even have engaged into the research. Industry equally needs to understand this point, as they might need to provide funding to bridge these gaps.

Industry facing research in methods cannot be conducted in isolation from the development of the underlying design theory as well as the evolving technology. As such, the research must span all the way between pure theory-building and

minimal-scope technology application. Therefore, the development of methods and the associated funding must plan this in to grow the field at large.

## 4. Implications

We expect that this paper and the expressed opinions will cause reactions – agreement as well as disagreement. We hope that this will stimulate a constructive debate on the subject and will help to improve the relevance and impact of our research and ultimately to improve the outcome of engineering work, thus contributing to the better of our society. We need a joint debate about what academia can provide and what industry needs.

The opinions expressed before would require a change of course in the design research community in several ways:

(i) We have to open up the design research community further. Given that design practice is expected to become more multidisciplinary and given that design processes (as prescribed as well as executed) have characteristics that are mutually dependent with the product/system that is being developed, the research community needs to actively attract experts from other engineering disciplines as well as other disciplines outside classical engineering. Moreover, we need to attract researchers from different fields and encourage them to use design as an application field for their own challenging questions. At the same time, we need to develop respect for the domain expertise of other fields, such as psychology or computer science, and not assume that design researchers can pick this up easily. Academic societies should more actively reach out to other scientific communities and establish ways to foster the exchange.

(ii) We need a better dialogue between the research community and industry, that goes beyond individual researchers working with individual industry experts. The exchange between academia and practitioners – in whatever form – would benefit from a more intensive participation of practitioners in academic events. The research community should develop alternative formats that provide value to its different stakeholders and should evaluate to what extent existing formats need adaptation (without reducing value for its current core-membership). In particular, we need a platform in which academics can exchange case studies and other descriptions of practise, which currently exceed the word limits of same journals and are not seen as sufficient contributions by others.

(iii) We need more work on underlying notion and concepts of design to enable us to engage in a dialogue rather than talking past each other using the same words, in a similar way to the scholarly work. Rather than highlighting the common elements, we need to analyze the differences to help us with the assessment of the scope and applicability of methods and to assess the implications of the methods that we are proposing.

(iv) We need to develop a code of practice around publications of immature methods, which enables industry to clearly identify well developed methods while allowing an exchange of ideas of our researchers. In particular, we need to encourage journals to value publications on the consolidation of the existing methods and the application of methods, which are currently often rejected because the reviewers see them as not sufficiently novel.

An ecosystem of methods needs communities of practice that have a shared understanding and can work together. We need to move beyond individual initiatives and personal contacts to create networks amongst researchers and industries. There are multiple examples of what has worked to achieve this partially in the past. They discuss tentative ideas, give each other feedback, attend each other's events and give each other a chance to try out research. It is a role of the academic communities and professional societies to foster these kinds of networks, through events organized by special interest groups, industry participation at conferences or training offered for industry.

This points to another debate which the design research community needs to have around the rigor of design research. As a community we aspire to rigorous research and demand a high degree of validation of our research. However, in practice, many of our publications do not include a validation of the presented work. While this is not necessarily a problem in general, it is one for methods, since it undermines our credibility with industry.

To reach a greater synergy between different methods, it is necessary that academic researchers engage deeply with other proposals and articulate clearly where the similarities and differences and respective advantages lie. Finding a common ground in a first step to developing an ecosystem, as well increasing the academic rigor of the work. In Section 2, we have broken the concept of a method down into its constituent parts: the core idea, the representation, the procedures and the method description.

The core idea of a method (i.e., 'the basic principle, technique or theory that the method employs'; Gericke *et al.* 2017) expresses the fundamental take on the problems it addresses, however the development of a method that can really be used requires multiple rounds of refinement of representation, the procedures and description. To get this right so that the methods can be used requires serious and collective effort, which needs to be recognized as research in its own right. Fundamentally, different core ideas are rare. A new one should only be proposed, if it could be thought of as a new paradigm or school of thought. Otherwise, we should acknowledge the common idea and build up a joint body of knowledge. It would be far clearer for industry and other researchers, if new research was presented as a significant advancement of a school of thought rather than yet another way of working.

As a community we therefore have to step up both academic rigour of our work and the depth of engagement with our user community: industry.

## 5. Conclusion

Design research is impacting design practice which goes beyond the pure uptake of individual methods. Using the uptake of all the methods proposed by academia as a success criterion is too narrow-minded and is unrealistic. As design researchers we advocate an innovation funnel concept for successful product development, where only a small percentage of the initially developed ideas will ever make it to market. The critique regarding the lack of uptake of design methods by industry seems to imply that this metaphor does not apply to the products of design research. When discussing the impact of our research, we need to deliberately manage expectations to avoid fostering a perception of design research, which is detrimental to our

ambition to support industry. As a community we succeed if some of our methods make a difference to industry.

The impact of design research is created by different means – first of all through the students that are trained based on the research results including design methods and tools and by the systematic way of thinking they acquired that comes along with being involved with research in this area. The students impact design practice in a slow but sustainable way. The other form of impact comes from the direct transfer of methods to practice.

While training the next generation of engineers is a powerful pathway to impact, it is important to also improve the way research results are transferred directly to industry. Therefore, it is important to accept the realities of industrial practice, such as methods and tools are embedded in an ecosystem of methods. Not all methods are applicable in all circumstances and often methods have to be adapted to the contextual needs of practitioners. Moreover, we need to train students and practitioners to perform such adaptations of the 'textbook' versions of the methods we propose.

An improvement of the direct transfer will ultimately allow us to feedback experiences and changing needs into the continuous improvement of methods and training of the next generation of engineers. Such an improvement will make this feedback much faster, thus helps to avoid lagging behind what industry needs. This is a task that requires collaboration of academia and practice as both will benefit from it.

Using feedback from industry as an enabler for a dialogue that informs the continuous improvement of design methods implies that we should question if the ambition to support designers always requires the development of new methods. Maybe, we have enough methods and should instead focus on improving and adapting them. Refining a method is a long journey of many improvements, for which only few researchers have the time, passion and resources. Being able to adapt them according to the context-specific needs of practitioners requires a deep understanding of design practice which we have to develop. What is required is a healthy mix of refinement of existing methods and development of new methods that complement the existing ecosystem of methods.

Improving and developing methods that fit into an ecosystem requires thinking about the whole design process not just the individual design activity that is primarily supported. It requires us to think beyond the individual method to understand its dependencies and interactions with other members of the eco system. Understanding the relationships, a method has within the ecosystem, requires to clearly assess and articulate the scope and impact of each individual method. This, besides other means, will allow us to move from owning a method menagerie to effectively contributing to the evolution of method ecosystems in practice.

As an academic community we need to learn to acknowledge incremental development of methods as a contribution to the body of knowledge of design research. This includes welcoming publications on industrial practice which sets the context for methods and publications on increments of methods.

As an academic community we need to work on the channels for communicating with industry. We have to rethink established channels but also to develop new channels or utilize channels that exist in other fields.

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**Title of the Presentation:**

The Simonian tradition in design (economics, information, learning, decision, branch and bound algorithm, problem solving tradition)

**Synopsis:**

This course presents the main thesis of Herbert Simon in design (operation research, search algorithm, branch and bound algorithm and problem-solving). In addition, this tutorial will highlight the impacts of this research on the evolutionary and behavioral theories of organizations. Finally, the limits of this approach will be presented.

**Main References/ Further readings:**

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# Cognitive Processes and I11-Defined Problems: A Case Study from Design.

**Conference Paper** · January 1969

Source: DBLP



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# COGNITIVE PROCESSES AND ILL-DEFINED PROBLEMS: A CASE STUDY FROM DESIGN*

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## Summary

In this paper the information processing theory of problem solving is extended to include ill-defined problems. A protocol of problem solving in architectural design and its analysis is presented. The significant difference between well- and ill-defined problem solving is shown to be a specification process similar to information retrieval processes now studied in artificial intelligence. A variety of issues in this retrieval process are examined. The search process involved in the space planning aspect of design is shown to correspond well with existing formulations of search. The interactive effects of retrieval and search processes are examined.

## Introduction

All problems can be said to consist of translating some entity (A), into some other entity (B), which is specified in terms of goals to be achieved (A -► B). The major efforts of problem solving theory to date deal with problems where A, the initial problem state, →, the operators available to alter the problem state, and B, the goals to be achieved, are specified, either explicitly or by some agreed upon formal convention'. Thus detailed analyses have been made of how people determine chess moves, how they solve geometry, word algebra, and crypt-arithmetic problems, and how they solve logic proofs[2]. While some are less well-specified than others (in chess, the goals for evaluating a specific move are open to individual interpretation), all of the tasks thus far analyzed have an operational formulation. Such problems are considered to be well-defined.

This paper describes efforts to extend the information processing model of problem solving to those problems where part of the problem specification is lacking. Of interest are those tasks where a formal language for describing the problem space, operators for moving through the problem space, or the precise expression of an acceptable goal state is not given. In such tasks, the problem solver must specify the missing information before search of the problem space is possible. Such problems can be called ill-defined.

An example of ill-defined problems are the space planning tasks found in engineering, architecture, and urban design. Space planning can be defined as the selection and arrangement of elements in a two- or three-dimensional space, subject to a variety of constraints and/or evaluation functions. Space planning problems lack a well-specified language for their representation. The generative transformations available to the problem solver for manipulating a design are not known. Most such problems also lack a precise formulation of an acceptable goal state.

This paper presents a detailed analysis of one example of ill-defined problem solving. The problem is a space planning task commonly found in architecture, the selection and arrangement of elements in a room. Evidence from this analysis is presented which advances two hypotheses: (1) the major distinction between well- and ill-defined problems is the assumed availability of a specification process for defining the problem space and goals of a problem. Ill-defined problems are subjectively specified; (2) if the specification process is the major distinction between well- and ill-defined problems, then a complementary hypothesis would be that the search processes used by humans to solve both types of problems would be similar. The motives behind these efforts include gaining a better knowledge of those processes which society has traditionally called "creative." Such studies may also provide the foundations of a method for automatically solving ill-defined problems.

## Psychological Foundations

The psychological premises of these studies are similar to those involved in the work of Newell and Simon, E. B. Hunt, and many others who use information processing concepts to study concept formation and problem solving[3]. The best descriptions of these premises are found in Miller, Galenter and Pibram's Plans and the Structure of Behavior or in Walter Reitman*s Cognition and Thought[4].

The model proposed is as follows. Thinking is information processing. The sources of information may be the environment, the physiological state of the individual, or his memory. Memory is interpreted as allowing independent recall of past environmental or physiological states and recall of past Intermediate processing. Cognition--or thinking—is the resultant of specific information being brought together in a unique combinatorial sequence. In this light, a problem situation is unique because a specific response to a set of inputs is not directly available. At issue is the selection of appropriate inputs from memory or from the environment and the search for their possibly unique combinatorial sequence. The processing that cognition and problem solving Involves can be modeled as a series of transformations generating a

* This work was supported by the Advanced Research Projects Agency of the Office of the Secretary of Defense (F 4460-67-C-0058) and is monitored by the Air Force Office of Scientific Research.

sequence of Information states. The total number of states generated by applying all permutations of applicable information to all information states defines the total problem space. The means used to sequentially generate information states so that one is created that satisfies the problem goals is called the search strategy.

Information processing, whether it be in man or machine, can only be achieved when the relevant information is in an appropriate processing language. Processing languages provide the operators necessary for combining information. Well specified processing languages include computer programming languages, algebra, symbolic logic, and other calculi. The processing language used in human cognitive processes has not been identified. Human problem solving theory has proceeded on the assumption that the well-specified processing languages listed above, since they are used by man, are partial subsets of the formal language internally available to him. Problem solving tasks have been analyzed in terms of the problem spaces and operations available in these languages. In the past, problem solving analysts have limited themselves to those tasks where some well-specified formal representation was available.

Problem solving analysis usually takes the form of studying how a problem solver treats a special task assigned him. Generally unreported in the literature, yet a common occurence in most actual experiments is the problem solver's difficulty in understanding the task exactly as it is conceived by the analyst. The problem solver's initial assumptions are different and require correction before the experiment can proceed. This problem points out the fact that problem solving analysis Involves the comparison of two parallel processes. From the explicit problem statement both problem solver and analyst identify the goals to be achieved and elaborate them as needed. Both either assume or select a processing language to work in and within it devise various strategies for exploring the problem space thus created. The analyst can understand the problem solver's processes to the degree that he can find correspondence between the processes he has experienced and thus understands and those of the s. Fruitful analysis requires the analyst to ha"ve processed significant portions of the problem space so as to maximize these correspondences. To further maximize such correspondences, only problems that allow the analyst to make strong assumptions about the goals and problem space used by the problem solver have normally been used. Yet the difficulties of the s in understanding the analyst's conception of the task emphasizes the variability in the processes by which tasks can be specified.

If the assumptions of parallel processes and the search for correspondences is applied to the specification of problem goals and a processing language, this aspect of processing also should be amenable to analysis. It need not be predetermined.

Like most studies of human problem solving, the method used in the studies reported here consisted of giving a Subject *(S)* a complex task and recording his expressive behavior while solving the problem. Detailed records of sketches and verbal behavior were carefully collected. Other potentially significant behavior, such as facial expressions and looking at objects as a source of auxiliary input, were also recorded. Together, this information made up a protocol from which the internal processing of the S, could be analyzed[5],

## The Task

A typical small scale space planning problem is shown in Figure I. It asks a Subject to redesign an existing room so as to make it "more luxurious[11] and "spacious" and sets boundaries for the solution in terms of cost.*

This particular task is ill-defined in at least two ways. No existing formal language can adequately represent space planning problems. While the informal representation for such problems is orthographic projection, the elements of this language, its syntax, and rules for generation or manipulation are unknown. These aspects of the representation are left to the problem solver to intuitively identify. Another ill-defined aspect of space planning problems in design is the identification of problem goals. The problem in Figure I is typical in that no specific information is provided as to what a satisfactory design should consist of. Generally, design tasks have as their explicit goal the specification of some physical entity in a form allowing construction. Left implicit are many criteria the specification must satisfy. It is assumed that the engineer, architect, or city planner solving the problem is familiar enough with it to know what specific elements are to be included in the design and their function. From his background, he is expected to be able to identify the goals which apply to various selection and arrangement possibilities.

Many protocols have been collected from this particular task. Some were presented in an earlier report[6]. A new protocol gained from this task is shown on the left side of Figure II (which continues for several pages). The s of the protocol was a twenty-six year old industrial designer, who was attending graduate school. He had two years of professional design experience. Approximations of the figures drawn by this s while solving the problem are included in the protocol. It is broken into sections, each of which corresponds to a protocol minute (PM).

* The particular task presented here, the design of a bathroom, was chosen because of its general familiarity to a wide diversity of people both within and outside of the design professions. Its use here was not to gain detailed information concerning the solution to this specific type of problem but to learn more about the method by which a human deals with common yet problems.

Essentially, the S presented here created an alternative design for the bathroom by identifying and satisfying goals from his own experience as to what a good bathroom design should be. Privacy, a neatly ordered appearance, adequate circulation and access, short plumbing lines, and low cost were the most evident concerns. While generally there was more emphasis on identifying design goals early in the protocol and on search for an arrangement at the end, both processes were highly intermixed. In all, five alternative bathroom designs were created and evaluated. Only two were completely developed. Figure III presents the general sequence of processing described in the protocol. All external processing took place in a plan drawing representation, except for a short sequence which utilized a vertical section. The total processing time was forty-eight minutes.

## Task Analysis

Ill-defined problems are without a predetermined language or explicit goals. The initial requirement for analyzing ill-defined problems is Identification of these aspects of the problem solver's processes. The general identification of goals and processing languages turned out to be straightforward for the example protocol and was achieved by scanning it for the following types of information:

1. All physical elements that were considered or manipulated during problem solving (what we call Design Units (DUs));
2. All information that was used to test or determine a design arrangement or selection of a DU, or any information used to derive such information. This information was assumed to identify the problem goals;*
3. All operations that produced new solution states. A solution state was considered to consist of the current arrangement of DUs and current information about the problem. A change in either the arrangment or the information available was considered a new solution state.

The information that was identified is listed in Figures IV and V. These listings give an interpretation, in verbal form, of all information which evidence suggests was processed during the problem solving described in the protocol. Much of it was never verbalized, but was only silently applied in some manipulation within the problem. Other information was mentioned but its use never verified. This information has not been listed.

In our terminology, a constraint is a function applied to a solution state and returns a boolean evaluation. An evaluation function is a function whose value continuously varies with its state, A goal is the general name for both evaluation functions and constraints. A consideration is information used to derive a goal.

Corresponding to each section of the protocol and to its right is a detailed description of the processing that transpired, coded in terms of the information listed in Figures IV and V.

Our knowledge of design methods allows us to correctly anticipate orthographic drawings as the processing language used in searching for a satisfactory arrangement. This intuitively defined language seemed to be automatically assumed by the S. Alternative formal descriptions of the operations, element, and syntax of orthographic projection have been developed and presented elsewhere 7. They will not be elaborated here. The operations and language used in the selection of DUs and identification of goals was not orthographic projection, but took quite a different form.

Even though the protocol did not present search and problem specification processes as disjoint processes, the following discussion initially considers each separately. This approach allows existing knowledge about each of these processes to be brought to bear on the protocol. Following individual consideration, their interactive and confounding effects are considered.

### Goal and Design Unit Specification

Given the partial specification of a problem, a problem solver has available at least two means to complete it. He may: (1) disambiguate the given specification and attempt to identify subtle or implicit information within it, or (2) re-identify the problem using his own perceptions of the initial situation. Both approaches are used in design. The first approach predominated in a previously presented protocol, gained from the same task used here[8]. The S. in the included protocol, in contrast, chose to re-identify the problem.

In order to understand the processes by which the S specified DUs and goals for the problem, an attempt has been made to intuitively reconstruct two portions of his specification process. The sequence in which information is expressed has been identified so as to suggest what kinds of processes may be generating it. In recording the sequences of processing, simple diagrams are used. They should not be considered literal models of the internal data structures being accessed, but may be serve to suggest some properties of those structures.

In an early part of the protocol, the S is told that the design he is to generate should respond to the needs of children (see PM2). Soon afterwards, he recognizes a need to store bath-towels and children's dirty clothes. He also relates dirty clothes to the location where they are cleaned - the washroom - and wonders about the distance between it and the bathroom. He suggests that temporary storage for dirty clothes might be needed. Much later (PM21), this line of thought is picked up again and the recognition made that a clothes hamper would be a positive component of the design. This information is generated when the utilization of storage space is being considered. The sequence of associations

made is presented in Figure Via.

What seems to transpire here is a sequence of thinking ending with the identification of a particular Design Unit relevant to the problem.

Another example of an association process is seen at the very end of the protocol (PM47). Earlier, the s was told that the window was of the operable variety and that it contained frosted glass. The S in the current sequence is considering the detail design of the storage cabinet located in front of the window. While working on the cabinet, he identifies that it may be difficult to close the drapes in the window. This seems to have been achieved by recognizing the distance between the clear floor area and the window. See Figure VIb.

In both these sequences, information from the environment (e.g., from the Experimenter, the original design, or from the problem statement) is related to original information generated by the j>. No other source for this new information is possible. In both examples, several pieces of information are generated and related with those that are given before information of specific relevance to the problem is generated. The first sequence identifies a new DU; the second identifies a constraint. The two examples are the longest sequences of related information that produce design information. Thus they are the most explicit. Sequences of unitary length are common (see PM5, PM11, PM15, PM33).

The processes which produce such information might best be considered and examined for potential modelling as information retrieval processes operating on a large base associatively stored memory. The given problem information is the initial queries into the system. Sometimes a desired access is not initially made; only further inputs allow isolation of relevant design information. Most further inputs are gained from cues identified while processing other parts of the problem. By mixing information retrieval with arrangement processes, new access queries can be identified and used to reinformce those made with the originally available information. These additional cues seem to allow accesses that no single inference making capability could match.

Only a few insights are offered as to the detail structure of this system. Some evidence suggests that the major elements of the retrieval system are physical elements (e.g., DUs, people - most generally, nouns). These are the aspects of the information that are expressed most often and which seem to gain elaboration from further processing. The structure between these nodes cannot be identified from the protocol data. Most reasonably, they would be verb and prepositional phrases. Such a structure is supported by recent work reported in the psychological literature.[9]

The DUs identified by the took one type of organization during one phase of processing, only to take another later on. These different definitions were not disjoint, but rather overlapping in a set-theoretic manner. For example, during major portions of the protocol the toilet-tub was manipulated as a single element. Later, though, it was treated as two separate elements. At one point the bathtub was further decomposed into its components. Each element thus had the possibility of being broken into the elements of which it was a set. The hierarchical decomposition thus produced is shown in Figure V.

The purpose of composition or decomposition of DUs is essentially one of search efficiency. Decomposition widens the solution space by allowing a greater number of primitive DUs to generate a greater number of design alternatives. This is useful when the current solution space is too restrictive to easily find a solution. Alternatively, composition narrows the search space. Composition is especially applicable to sets of DUs which are relatively non-Interactive with others and can be arranged so as to satisfy the interactive goals or constraints within the set]$^{0}$ The bathtub-watercloset combination in the protocol is an excellent example of the use of composition. An information retrieval system useful for design problem solving would need the capability of composing and decomposing DUs.

The issue possibly raised here and elsewhere as to whether information is stored discretely in the agglomerated concepts used in the given description and protocol analysis is easily resolved. In all memories known, a trade-off exists between the alternatives of explicitly storing large amounts of data and possessing a process that dynamically generates the information when it is needed. If this trade-off exists in a memory, then the modelling of that memory can reflect this trade-off also. It may be most expedient at any level of model building to assume that information is explicitly stored. But a single node in a model at one level of organization may represent a whole pattern of processing at another level. The only requirement that is logically imposed is that information processing, at some point, pass through the state defined as a discrete element in any model. The value of the particular points chosen is determined by the parsimony of the description allowed.

The implications gained from the analysis of this and other protocols is that human performance in retrieving information from memory for application to ill-defined problems is quite limited. In space planning, a retrieval rate of one piece of applicable information per minute was exceptional. The size of memory required to intelligently solve a class of ill-defined problems is only now becoming known. That size seems to be smaller than expected. The eventual development of automated problem solvers may actually benefit from a memory even more limited than the size implied as necessary from human protocols. The controlled input of new information could delimit the data base to verified information, eliminating much questionable data. An initial exploration of an automated design retrieval system has been made by Moran.[11] More extensive models of memories capable of the kinds of retrievals required here have been developed by Green et al and Quilllan.[12] No model of memory developed thus far can perform, both in speed and diversity, in a manner similar to that described in the

protocol. No model has yet been proposed that takes advantage of auxiliary inputs gained from intervening processing. The interaction of search and retrieval processes may offer major benefits to large base associative memories.

Search Processes in Design

When faced with the problem of arranging elements in a predefined space according to some partially specified goals, all designers thus far tested have used a modus operandi for generating solutions that included as its main activity the sequential selection of both a location and a physical element to be located. If the DU could be located in the proposed location and an evaluation of the current total configuration was successful, then a new element was added to the design. If the evaluation failed, the current element or another was manipulated. Such operations can be viewed as transformations in a problem state space according to the traditional search paradigm. Examples of this sequence are evident in Figure III as sequences of intermixed tests and operations.

Space planning aspects of design' problems seem to fall within the transformational paradigm of heuristic search according to the following formulation. A apace planning problem can thus be defined as a

$\{a\} \equiv$ a space,

$\{b_1, b_2, b_m\} \equiv$ a set of elements to locate in that space. (Some elements may be defined as any member of a set.),

$\{c_1, c_2, c_n\} \equiv$ a set of constraints delimiting acceptable solutions and possibly evaluation functions to be achieved,

$\{d_1, d_2, d_p\} \equiv$ a set of operators for manipulating elements within the space, and

$\{e_r\} \equiv$ the current design state.

Each transformation consists of a triplet consisting of the current design state, an element to be operated upon, and an operator. Each transformation is made in an environment defined by all or a set of the goals to be achieved. Thus

$$\{c_1, c_2, c_n\}(e_r, b_m, d_p) \rightarrow e_{r+1}$$

The problem is to locate the elements within the space in an arrangement that satisfies the constraints and optimizes the evaluation functions.

Obviously needed is a process or method that selects an appropriate operation and an appropriate DU on which to operate. Highly diverse methods are possible. Algorithmic methods include lists or stacks of Design Units or operators. More complex operations usually include feedback from the current or past states of the problem. Processes that include such feedback are called heuristics [13]

The protocol included here, like others analyzed, show few examples where all combinatorial possibilities are exhaustively searched. Instead, all protocols showed reliance on a wide variety of heuristics. By a heuristic is meant a relation between some part of the current problem state and some part of the desirable next state. Most models of heuristics have framed them as productions in a Markov system.14 The production takes the pattern of

condition ⟶ response

If the left hand side of the condition is met, then the right hand side is applied to determine or partially determine the next transformation to be made. In the heuristics found in design problems, the left hand side is commonly a single DU or a constraint, or possibly a doublet made up of both a constraint and a Design Unit. The right hand side is commonly an operator, a Design Unit, or both. Examples of heuristics used in the accompanying protocol are CI9, which looks for uses of empty space, and C24, which identifies space for locating towel racks. CI9 has as its left hand component a test which checks for the existence of a space bounded on three sides and adjacent to the major space in the room. When a situation exists that meets these conditions, the right hand side of the production searches for any DU that may make use of the identified space. The left hand condition for C24 is the existence of a bathtub or sink. The right hand side searches for empty vertical wall space. Upon finding it, a towel rack is located. It may be repeatedly applied. The value of heuristics is that they orient the range of possible future solution states in directions that have been found empirically to be fruitful.

A schematic flow chart of the process outlined in the above formulation and described in the protocol is shown in Figure IX. This process corresponds closely with other formulations of heuristic search.'[15] Heuristic search is not the only search process used in space planning. Occasionally, generate and test and hill-climbing have been observed in protocols. But the main process relied on in the intuitive solving of space planning problems seems to be the one outlined here. Great individual variations within this general paradigm exist, in terms of the heuristics used and in the definition of the search space, as specified by the composition and decomposition of DUs.

The Confounding of Specification and Search

Throughout the protocol, search and specification operations were highly intermixed. No clear cycling or other separation of activities was identified. The value of such intermixing for retrieval processes has already been proposed. But intermixing is not without its costs. Confounding of retrieval processes also result.

An exceptional example of confounding is shown in PM7. At this point in processing the *S* is at a particular solution state that will be achieved again. At this state he asks for Information about the minimum distance between a wall and the front of a sink. Looking in Graphic

Standards (an architectural reference), he finds a wide variety of other Information. This Information distracts him from his original search and his processing takes off In another direction. Much later (PM37), the S has the same solution state represented and asks the same question as he did earlier. This time he gains the information he desires and generates a particular new state.

In this example, new information destroyed a search sequence originally developed by the s. It was only fortuitous that he was able to pick up the same solution state later. It seems that the control system monitoring search and retrieval processes is fallible - at least in some problem solvers - and that this intermixing of processes places demands on processing that can lead to errors. Other examples of confounding have been observed, though they are rare. Designers seem familiar with such aimless processing, having such names for it as "playing with the problem", "daydreaming", etc. The implication is that significant overhead costs accrue from effectively mixing search with specification.

## Conclusion

In this study, ill-defined problems such as those found in architectural space planning were shown to be tractable in analysis if they were separated into their information retrieval and search aspects. The task of operationally specifying a problem was proposed as the major distinction between ill- and well-defined problem solving. Some suggestions as to the structure and capabilities of an automated problem specification system have been made. Also presented is a formulation of the search aspect of space planning problems. It is suggested that the search and specification processes together can completely depict a large number, if not all, of those problems now classed as ill-defined. By further delineating the specification and search processes of problem solving, greater intelligence and creativity may be allowed to be built into future computer programs.

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EXPERIMENT NUMBER TOW

The accompanying plan and photograph represent an existing bathroom plan for one model of a home sold by Pearson Developers in California. This model of house has not sold well. The sales personnel have heard prospective buyers remark on the poor design of the bath. Several comments are remembered: "that sink wastes space";"I was hoping to find a more luxurious bath". You are hired to remodel the existing baths and propose changes for all future ones, (these should be the same)

The house is the cheapest model of a group of models selling between 23,000 and 35,000. It is two stories with a ranch style exterior. The bath is at the end of a hall serving two bedrooms and guests.

You are to come up with a total design concept. The developer is willing to spend more for the new design -- up to fifty collars. For all other questions, Mr. bastman will serve as client. Me will answer other questions.

*A* round vanity makes the most off a square-shaped bathroom

It permits two lavatories in a minimum-size countertop. And it also lets two people use the sinks at the same time without getting in each others' way. Extra shelves are set between the lower cabinets

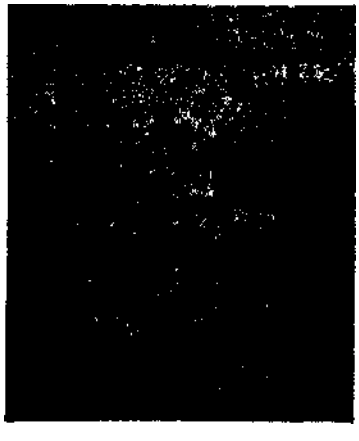


FIGURE I

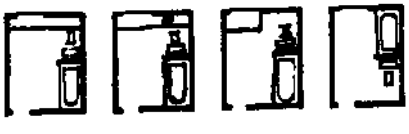
Experiment Two
Subject Number Four

February, 1967

| PROTOCOL: Experimenter's remarks in parentheses. | ANALYSIS: |
|---|---|
| PM1 (This sheet here represents the design project. It is self-explanatory. For all questions, I'll act as the client. Here's scratch paper, some blank, some with plans on it. You have about forty minutes to work.'). . . . . I would first of all like to know if you had brought in other comments than the fact that the sink would waste space and the bathroom was not luxurious. ('There wasn't enough storage space. The two sinks were appreciated. These were comments.') Yet they also made a comment that the sink wastes space. | Reads CI.<br>("Sink wastes space" is never utilized.)<br>Given C4.<br>Given C3. |
| PM2 ('Also from sales most buyers of these homes have young children. There is another bath--off the master bedroom.') Is the other one a two sink arrangement too? ('The other is small and has one sink.') Was there any remarks about privacy? Where does this door lead to— the hall or? ('Hall. You can see in the plan.') | Given C5.<br>("Other bath" never utilized.)<br>Retrieves C13 from memory.<br><C13 - C14> |
| PM3 The developer's willing to spend more for the existing design, up to fifty dollars. (Writes down "50.00".) I think that this statement about hoping to find a more luxurious bath.. This is a partition that can be removed, I take it. (Refers to the one at the end of the tub.) ('Yes'.) Can we move the fixture around? ('Yes'.) | Reads C2.<br>[CI]<br>Identifies DU12.<br>Removes DU12.<br>Given C6. |
| PM4 We can change the cabinet? ('Yes.') Looking at this and things that can be done, I think storage is important. I don't see where they can store too many bathtowels. Being that it is used by children, a large storage space for dirty clothes is also necessary. | Identifies DU4.<br>C4 ~ DU6<br>C5 ~C15 |
| PM5 I don't know how it connects on to the washroom. Perhaps for at least temporary storage until the time the clothes are washed. In the picture here, the cabinet does include some storage. This is a shower-bath arrangement. From what I CAN see, I'll leave this "luxurious bath" until the last. I'll try and work with these cwo elements as they are placed (e.g., tub and watercloset). What I can see is trying to slim down this area (e.g., in front of watercloset) and add some storage. I'm limited by the window. How high is the window? ('3' x 4' window, 6'-8" head, so it's 3'-8" off the ground.') | C15 ~ C16<br>C15 ~ C4<br><C4 ~ DU6c><br>DU6 ¢ DU4<br>Identifies DU3.<br>[C1]<br>Mentions processing strategy.<br>C19 x (?) Locates DU4.<br>Identifies DU12.<br>Location of DU6 ~ C17.<br>C17x.<br>STARTS ALTERNATIVE ONE |
| PM6 (Sketches figure A, lightly.) This partition here can come out. Location...Is this thing called a "john" by the trade or...('watercloset') right "W.C." and the tubs. We will | Removes DU4 and DU12, locates DU4.<br>Identifies DU2. |

Figure Ha

| | |
|---|---|
| maintain the two sinks. It seems that they are accepted. They just don't like the arrangement. | [C3] |
| PM7 It looks like we're going to have one more element to our already somewhat cramped space--a storage area. Do I have to talk while I'm drawing? ('If it seems natural, do so'.) You don't have a human factors book here? ('No. You are free to use Graphic Standards'.) I'm interested in spaces between, say, sink and a wall. ('Those are in Graphic Standards.) | [C4]<br>[DU6]<br>(Same question that is asked in PM36.) |
| PM8 Oh, okay. Let's see. (Looks in Graphic Standards.) Well, there's the answer. I'll just use Number Three here. Laugh. So, a double sink and I don't have the...I would like to have how wide these sinks are. They're completely round? (*The sinks are 19" in diameter to the stainless steel trim/) Nineteen inches, placed side by side with space in between makes..(Locates first sink as in Figure B.) My first thoughts about the sink | Given C7.<br>Locates DU5. Identifies CI8, [C18*location of DU5.] |
| PM9 are that instead of being placed back to back with a double mirror, they will be placed side by side with a full length mirror running in front, with the addition of work space between the two, with the full length mirror running across them. Or perhaps you could use these two mirrors with the detail between them removed to keep the cost down. | Explains operation.<br>[C18]<br><C18 ~ DU8> |
| PM10 ('The fifty dollars additional cost allowed is fifty dollars above all costs for the current design. It's not necessary to be concerned with remodeling this one. We're concerned with those still to be built'.) Oh, good. Well, initially, I think I prefer having the storage go beneath the window, A low storage cabinet. Just by looking at the space--it would be a low storage cabinet that goes just beneath the window and flush with it. | [C2]<br><C11 x (Removes DU2).><br>CI9 x DU4 "I prefer storage beneath window".<br>Identifies C20. [C20*location of DU4.] |
| PM11 The window looks awfully high in the photograph. It would be, according to standards, probably about 18" deep....(Alters sketch as in Figure C.) This is primarily a space | Identifies C33. C33 x (design fails.)<br>Locates DU4. No room for DU5. |



a. b. c. d.

Figure IIb

| | |
|---|---|
| problem, as I see it. (Alters sketch as in Figure D.) It's a matter of moving these elements aroung to get the best location. I do like the idea of this type of arrangement where the tub and the watercloset are back to back, because then the shower. | <PU1><br>STARTS ALTERNATIVE TWO<br><C2 ~ C21><br>C21 x DU1. "I Like this. .arrangement. |
| FM12 I think it's a good way of putting the shower pipes. The two sinks will...Let's see, what is the distance from...you said the window was 3'-4" square ('No. 3' by 4'.') Oh, four feet wide. That leaves five feet. | Identifies C22, not CI2 for use in front of bathtub.<br>Measures tub to far wall. |
| PM13 That's three foot six across...Would the window have to stay where it is? ('No. It could be moved.')...(Moves window, draws cabinet as in Figure E.) I'm trying to think what you'd do with a window in a bathroom. You generally have it closed off most of the time. | Measures window to wall.<br>C22*location of DU4.<br>C20*location of DU9. |
| PM14 Does this window open? ('Yes. Code requires it--or a fan.') You could have a non-opening window and a fan...but it'd be pretty stupid to put in a window that didn't open. (Adds to sketch as in Figure F.) There's enough room. The door opens in or out? | Given C8 identifies DU9.<br><C19*location of DU4.><br>Locates DU2. |
| PM15 ('In.') To the left or right? ('Left'.) Adds to sketch as in Figure G. Do they ever have doors that are hinged on the right? ('Sure'.) In homes? ('Yes'.) On either side, then...(Then as in Figure H.) | identifies C23. C13 ~ C14.><br>C14 and C23*location of DU10.(?)<br>C33*location of DU4 and DU5. |
| PM16 ....I'm now trying to visually locate these elements. Do they have towel racks within the shower? (No.') Okey. Well, they do now. How about the towels for this sink? Are they hanging on this wall? (Ves. On that blank wall. There are two towel racks on that wall.[1]) | Identifies DU13. identifies C24.><br>Identifies C25.> [C24 and C25* location of DU13.]<br><C24*location of DU13.> |
| PM17 Here's what my initial design is. I may have it a little out of scale....Here's what I have—my initial concept. I moved the tub—switched the tub and the watercloset around. | EXPLAINS ALTERNATIVE TWO<br>[ DU1] |
| PM18 I wanted the window moved over, just about—if I gave 12 inches on that side there probably about 2 inches from the wall. My reason for moving the window is that I'm putting this storage area that would start underneath the window and this would then be able to flush off with the window. It would create a more unified look to it and also provide the space necessary between the tub and storage area. | [Locates DU9]<br>[C22 x]<br>[C20 x]<br>[C22 x] |
| PM19 The fact that the faucets and stuff are up here will mean the tub will be used in this area | Retrieves C25 from memory.<br>[C25 x] |

Figure lie

| | |
|---|---|
| primarily. It will very seldom be used down here, The towel rack for the shower—there would be a towel rack on the end of this storage for this sink. There could be a towel rack on the storage or on this wall for it would provide plenty of clearance for this door opening. This initial problem is that you've got this much wasted space as far as storage (referring to corner storage area). This box down here could be additional storage. | C24* location of DU13.<br><br>Identifies C26. C26 x "This much wasted space.[11] |
| PM20 We're running—if we're limited to fifty dollars additional, we might find that the additional material here and here will take up that fifty dollars.... | C2 x |
| Okey, I would use here a full mirror that would run from this area in front of the two sinks. (Adds to sketch as in Figure I.) I would not use a medicine cabinet. The storage underneath the sinks could be used for this, or the top of this storage area. (Draws arrows as in Figure I.) This would all be the same height, of course. | [DU5]<br><br>No DU8.<br><br>[CI8 x] |
| FM21 The whole thing could be constructed as a single L-unit. This storage area would be useful (e.g., on the south wall). I don't know how neeessary it is. For kids, they could generally use a lot of storage area, used for perhaps a swing-out hamper, or something like this (adds hamper as in Figure I). Right now I have a "set" on this combination of the tub and the watercloset. In this particular design there would be a "quote--unquote pleasing vista when you look into the...outdoor naturally lit aspect. | C2 x DU6.<br>Identifies C34. C34 ~ DU6c.<br>[Locates DU6c.]<br><br>Locates DU6c.<br>[DU1]<br><br>CI4 x "pleasing vista[1]' |
| FM22 If it's at night it still has the connotation of being oriented towards nature. (Draws arrow as in Figure J.) This could be a rather pleasing unit, esthetically. It could be fairly clean. This is why I feel the tub and the watercloset have to be located on this side of the wall, or in this area. It will...the tub will fit going this way. | C14 x "fairly clean". |
| PM23 It's a five foot tub. That would give me | STARTS ALTERNATIVE THREE |

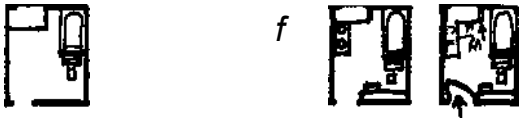


Figure IId e. f. h.

| | |
|---|---|
| enough for a four inch wall? ("Walls are 5.5 inches'). That wouldn't give me an adequate wall. How about moving the door? ('Within the confines of the possibilities—fine[1].) I was thinking of going to another possibility of putting the tub | DU3. Wall = tub = 4 inches.<br>Locates DU10.<br>C14 x. |
| PM24 .,1 think this is an efficient way of putting the plumbing into it. I think that..don't both outlets go to the same place? ('Yes'.) This could be an efficiency here. Would they still take down tow lines or would they connect it? ('In this case they would connect it. There's plumbing downstairs below here. Variations along this one wall adds no cost.') | GOES BACK TO ALTERNATIVE TWO<br>DU3.<br>C21 C21 x "Alt. Two efficient" |
| PM25 If I put my sink over here, then I have to put an additional amount of plumbing. But of course it's fairly impossible to put the sink and watercloset and everything on one wall—unless you have small people. Let me look at this other one and see if I could move the door. (Draws Figure K.) I really feel just by looking at this, the way they have the sink and the watercloset together is really fairly efficient—a good way of doing it | 57. C21 x "additional amount of plumbing",<br>GOES ON TO ALTERNATIVE THREE<br>Locates DU3.<br>GOES TO ORIGINAL SOLUTION<br>C21 xoriginal sol. "fairly efficient".<br>GOES TO ALTERNATIVE TWO |
| PM26 ....Now I'm trying to eliminate that corner of the shelving. (In Figure J.) It can't be used for storage very readily. I wonder if I'm making these shelves wide enough. 19 inches. That includes the faucets? (Usually a counter-top for a bathroom is 22" deep.[1]) | Given C9. |
| PM27 I haven't been making them wide enough... Let's see, twenty-two, oh, I imagine that would have to be a twenty-two inch area for the sinks, or very close to it...(Draws Figure L.) Ah, yes, now I'm trying to find a way to put all this plumbing along one side. | C9xall solutions, "not wide enough".<br>GOES TO ALTERNATIVE THREE<br>C21*location of DU2.<br>[Locates DU9.] |
| PM28 I've moved both the door and the window in this one. Ha! Diabolically I'm going to put a large full-length mirror here and the watercloset directly across from it. I imagine you wouldn't be able to sell this place that way. Okey, dressing area, this could be almost flushed off. We're still maintaining the same type of tub, is that right? | [Locates DU10.]<br>Locates mirror. (Joke).<br>C22 x. |
| PM29 Five foot-two inch tub? Let's see. The plumbing could be run up through the walls if necessary? This is just a shower curtain. So we have to provide a wall for the plumbing and shower curtain. | Identifies DU3a.<br>Retrieves C27 from memory.<br>C27*location of DU12. |
| PM30 It's becoming inefficient. Moving it this | C21 x"becoming inefficient' |

Figure He

way, it's beginning to look like my own bathroom, which is inefficient...The tub is against the wall, then the John is next, then the sink. This is what this is turning out to be. You can get a lot in a close space but it isn't very attractive. I want to maintain a fairly pleasant view that still says bathroom

PM31 but eliminates the more unpleasant parts of it, such as looking at the watercloset, or perhaps bathtub. Shower is here, the main area of the entrance...(Looks in Graphic Standards.)... I need two feet four inches minimum. And from the sink. I'm looking for the minimum area of a work counter space.

C14 x"eliminates the more unpleasant parts".

Retrieves CIO.

PM32 I guess there isn't such information. That leaves only two feet six inches, so that eliminates putting the watercloset in there at all. We could put it over here (on the opposite wall) which I don't go along with. So arrangement two which is trying to put the tub along this wall, masking it off to give a sort of hall effect, is not efficient. It provides a lot of space, but if you put the watercloset in there, it will cramp the work space. . . . .

Measures distance from drying area to counter. = 2'4".
Size of watercloset = CI Ox.

Locates DU2. C14 x "don't go along with".

ABANDONS ALTERNATIVE THREE

PM33 Could I ask a question about this "hoping to find a more luxurious bath." Could you fill me in on that a little bit better? What was meant by "a more luxurious bath?" What were their objectives. ('They have seen all kind of fancy things. Evidently this just didn't meet their expectations.')..I would imagine that a glass enclosure would increase the cost well over the fifty dollars. I was thinking of, instead of using a shower curtain, of incorporating a glass enclosure into the wall and extending beyond just a little bit.

[CI]

**REVIEWS FIRST ALTERNATIVE**
**<C1 ~ DU3b>**
**Identifies DU3b.C2 x.**
**Locates DU3b.**

**C14 ~ DU12**
**C14*location of DU12.**

PM34 ('It would cost about thirty dollars.') There's something about a plastic shower curtain as opposed to a glass enclosure. I think you get more than your thirty dollars in Just the looks of a more costlier solution. We're

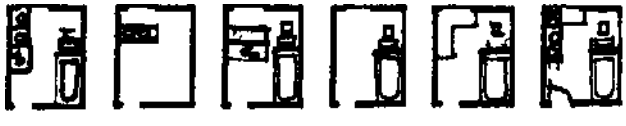
**C2 x (DU3a ≡ DU3b)**
**"more than your thirty dollars".**

Figure IIf **j. k. l. m. n.**

| | |
|---|---|
| talking about a twenty-three to thirty-five thousand dollar home. What's that old saying that your first alternative is generally your best one. Is that a true dictum? Well, we're going to attack this thing once more. | Reviews all solutions. |
| PM35 As far as the additional fifty dollars, it would not include moving the door and window? Right? ('Yes'.) So the fifty dollars is primarily in the addition of accessories, cabinetry and so forth. ('Yes'.) Well, let's see. I'm going to try it with the existing John and tub, as they are (Draws Figure M,)....I like the idea of being able to have natural light on at least part of you.... | Determine boundary of application of C2. '"Would not apply to door or window."<br>STARTS ALTERNATIVE FOUR<br>(Same as alternative one)<br>[C2.]<br>[Orig. solution] DU1.<br>Identifies C28. |
| PM36 (Adds to figure as in Figure N, then 0.) ...Can we assume that, say, between the wall and the sink tvo feet would be enough of an area to stand in? I don't see anything here. (Looking in Graphic Standards.) Here it says toilet is one foot six inches and two feet four inches between sink and tub. | C28*location of DU4. C7*location of DU5. C20 and C4*location of DU6.<br>BEGINS ALTERNATIVE FIVE<br>identifies C29.> C28 and C29*location of DU4.<br>Reads CII. |
| PM3 7 Then two feet four inches between tub and wall. But I don't see anything off the sink. Like here is down to one foot six inches. There's two-four. I don't see anything that has it close-up against the wall. Well, I'll operate under the assumption that of two feet to see what it'd look like. That is, to build sort of an island. (Draws Figure P then Q.) That's cramping up already. | Identifies C12.<br>Locates DU4 & DU5. C33*location of DU6.<br>Locates DU1.<br>C22 x "cramping up already". |
| PM38 Getting back to the same problem we had before....There's not enough room. What I've done,,what started me along these lines was if the sinks are by the window you could utilize some of the light. Then I thought, what would happen if the mirrors were actually facing the window? So that even if you had a head shadow there with diffused light | Explains alternative five.<br>[C28]<br>[C29] |
| PM39 it would be an additional source besides your incandescent light or flourescents which would be mounted over the sink. But, we're getting back to the same problem. Evidently,to have a floating unit or one standing out in the middle like this, you need more space to be able to work around it. Because by the time I put the thing out there, I haven't got the width. I was going to back this up with storage. I think the first design will be the best one. I seem to have a set for certain parts of the design. | Identifies DU11,<br>REJECTS ALTERNATIVE FIVE<br>RETURNS TO ALTERNATIVE FOUR |

Figure IIg

| | |
|---|---|
| PM40 I like the bathtub and watereloset in this position. They're efficiently related so as to take up little space and have efficient plumbing which can be in this one wall. Though there may be another arrangement which is better, like this one. (Draws Figure R, then S.) For storage, it would be required to have built-ins in the cabinets. They should be all we will need....I like the window and door being close to the wall. It looks less arbitrary. | [C21]<br>Locates DU1 and DU4.<br>C4 x.<br>C20*location of DU9 and DU10. |
| PM41 I think they could both be the minimum normal size. Again, I would like to utilize the view. (Makes site lines from door into bathroom.) (Adds to sketch as in Figure S.)... I'm worried about that wasted space here (in corner of cabinets). We need as much useful cabinet space as possible. (Draws Figure T.) | [C14]<br>C26 x"wasted space here".<br>C7 and C33*location of DU5.<br>Measures wall. |
| FM42 We have four feet of cabinet along this wall, which is satisfactory for two counters... I think this is about the solution I would offer, It has two sinks with more counter space than before. I'll keep the watercloset and tub like they were in the original design—but put a glass panel in above the tub. I want this tub here because it is out of the view from the doorway. | [C7 x] "satisfactory for two counters".<br>[C3]<br>[C8]<br>[Locates DU3b]<br>C14*location of DU3. |
| PM43 I might extend this wall around the watercloset to be flush with the "W.C." box (Adds to sketch as in Figure T.)...#I've added this "L" cabinet with a full length mirror five feet long. About a foot between sinks seems satisfactory with storage beneath. There's no medicine cabinet. All that sort of thing can go in the one foot area. Wait a minute! | C14*location of DU12.<br><DU5 ≡ DU6 ≡ DU5.><br>No DU8. |
| PM44 Why no medicine cabinet?.[1]! To have a cabinet in this design it would have to be five feet long and much too expensive. I could have a mirror and a floating element below it. It would extend out, say, about six inches..... (Draws Figure U.) We can't have six inches and only four inches clearance to the faucets. | Identifies DU7. Identifies DU7a.<br>C2 x DU7a "too expensive".<br>Identifies DU7b <C2x(DU7a≡DU7b).<br>USES ANOTHER REPRESENTATION<br>Locates DU7b.<br>Retrieves C30 from memory.<br>C30 x DU8b. "can't have..." |



o. p. q. r. s. t.

Figure IIh

The medicine cabinet must be about three inches—which is about their normal depth anyway. I've lived in places without a medicine cabinet . . . .

PM45 I'll consider putting a rotary tray in the center of this one foot area. Children won't have need for getting into the cabinets every-day. This storage area would stop at the window edge. That gives us plenty. (writes 2'x2x 2'6" =10). It totals about ten cubic feet total, not including the area under the sink.

GOES BACK TO FIGURE "T.
Identifies DU7c.
Locates DU7c.
C5 x.(?)
C20* location of DU6.
Measurements ≡.

PM46 It would be for towels and linen, etc. There's also semi-usable space for children's winter clothing in the corner space...Let's see. I guess sliding doors are more expensive than the regular kind. But if possible, I'd like to see sliding doors that go right into the space. At least one shelf would be circular, lazy susan type...(Adds sliding door and tray to Figure U, as shown.) Going back to the cabinet, I would put towel racks at the end of both cabinets. That would make them accessible.

Identifies DU6a and DU6b.
C2 x (DU6a ≡ DU6b).
? x
[Locates DU7c.]
Locates (DU7c and DU6a).
C24* location of DU13.

PM47 There might be a problem in closing the drapes. Usually in bathrooms, they are pulled closed without pull cords. But if the window's frosted glass, drapes seem a more decorative element. I'll leave it the same as it now is. The plan seems spacious enough, and offers clear passage to all the different fixtures.

Retrieves C31 from memory.
C31 x.
[C8 ]

[C22 ]

PM48 The towels might go on the back of the bath or maybe outside on this wall. That would be nice for guests, because you could show off your best towels in a highly visible place. . . . . I guess that's it.
48:50

[C24*location of DU13.] Identifies C32.

[C24 and C34*location of DU15.]

u.

v.

Figure Ili

SUBJECT'S BEHAVIOR GRAPH

Legend: I ≡ identify; A ≡ associate ; O ≡ operate ; T ≡ evaluate .

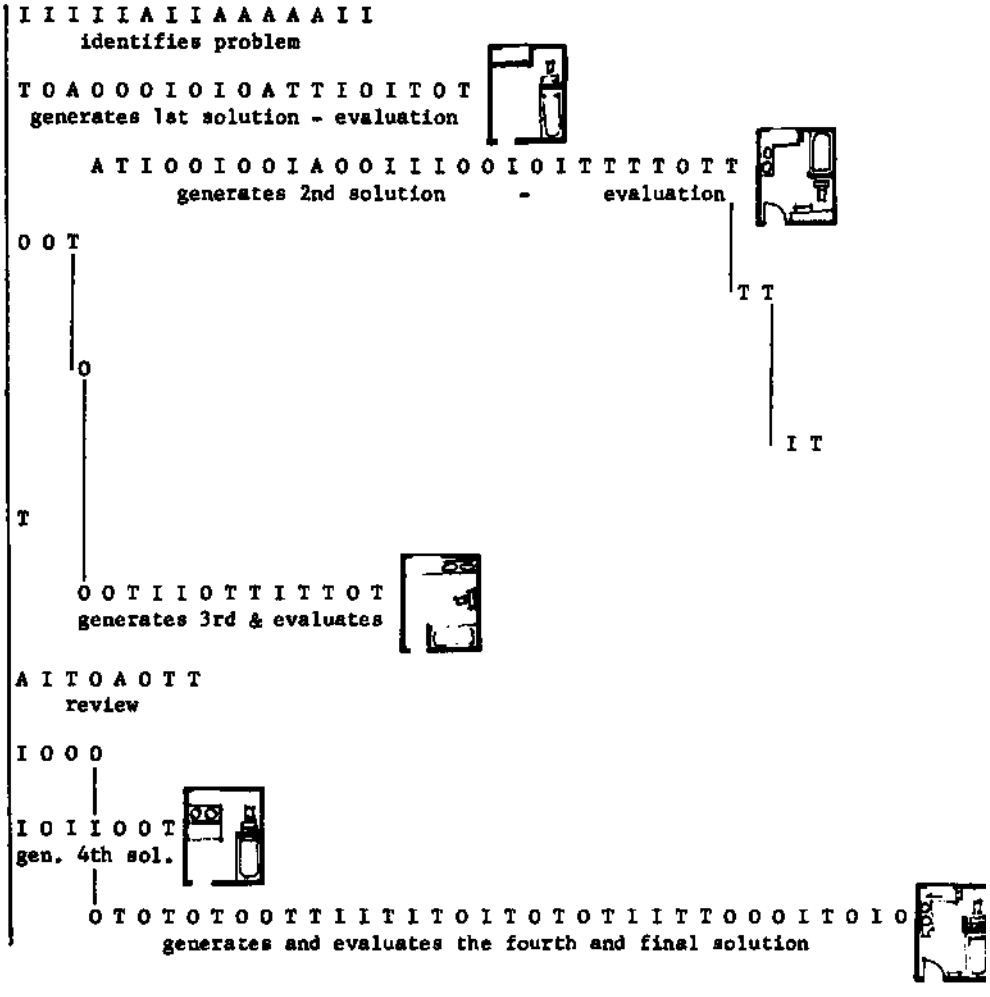



Figure III. Schematic behavior graph of processing carried out by the S. Time is in the direction of across the graph then down. Processing which begins with a partial solution or cycles between two solutions can be identified. Each symbol represents a transformation.

DESIGN CONSIDERATIONS, CONSTRAINTS AND GOALS

The following are written interpretations of the information utilized in specifying and resolving the problem.

Information Given in the Problem Statement;

C1. A more luxurious bath was desired.
C2. The redesign should not cost more than fifty dollars greater than the existing design.

Information Given by the Experimenter (Client):

C3. Two sinks are desired.
C4. More storage is desired.
C5. Most potential buyers have young children.
C6. Boundaries of the room should not be altered.
C7. Sinks take up about twenty inches of counter space apiece.
C8. The existing window opens and is frosted.
C9. Bathroom counters are normally twenty-two inches deep.

Information Retrieved from Other Documents:

C10. Bathtubs should have an adjacent drying space at least twenty-eight inches wide.
C11. Waterclosets require two feet clear space in front for their use.
C12. Sinks require about twenty-four inches in front for their use.

Information Recalled from Memory:

C13. Bathrooms require privacy.
C14. Toilets and bathtubs should not be directly exposed to the door.
C15. Children require space for their dirty clothes.
C16. Dirty clothes are cleaned in a washroom.
C17. Light from the window should be unobstructed.
C18. Free counter space is desirable.
C19. Some use should be found for every partially bounded subspace.
C20. Elements look well arranged If their edges align.
C21. Distances between plumbing fixtures should be minimized.
C22. Circulation areas must be wider than eighteen inches.
C23. Doors should swing open against a partition.
C24. Towels should be located on an empty vertical space near to where they will be used, e.g., sink and bathtub.
C25. Towels should be hung in a dry space.
C26. Storage space should be easily accessible.
C27. Shower rods need walls at their ends for support.
C28. Sink areas should receive some natural lighting.
C29. Light can be bounced off a mirror for added distribution.
C30. Area over faucets must be clear for their use.
C31. Curtains should be easy to reach for their operation.
C32. Some towels should be able to be displayed.
C33. Sinks should be so located that a mirror can be located behind them.
C34. To justify storage space, specific uses should be identified.

Figure IV.

DESIGN UNITS

Below are the physical elements which were selected and arranged during the problem solving sequence. They are hierarchically arranged according to the physical elements of which they are a part.

PUT: toilet - bathtub combination
- DU2: toilet
- DU3: bathtub
  - DU3a: bathtub with curtain enclosure
  - DU3b: bathtub with glass enclosure

DU4: counter
- DU5: sinks (including mirror)
- DU6: general storage
  - DU6a: storage with sliding doors
  - DU6b: storage with hinged doors
  - DU6c: clothes hamper
- DU7: medicine cabinet
  - DU7a: located behind mirror
  - DU7b: located below mirror
  - DU7c: located in the counter cabinet as a rotary tray
- DU8: counter work area
- window
- door
- light fixtures
- partitions
- DU13: towelracks

OPERATORS

The following operations were identified as processes described by the protocol. They are categorized according to what kind of data structure they operated upon.

Space Planning Operations:
- locate a DU
- remove a DU

Arithmetic Operations:
- s ::= numerical comparison or computation

Tests, as Applied in All Representations:
- X ::= evaluation of alternatives
- * ::« guides generation of locations

Semantic Operations:
- a~b ::- a is associated with b
- aeb ::= a is a component of b
- Identification operations are written out.

Context of Operations:
- .... ::= operation externally recorded
- [ ] ::= operation verbally repeated
- < > ::« implicit operation

Figure V.

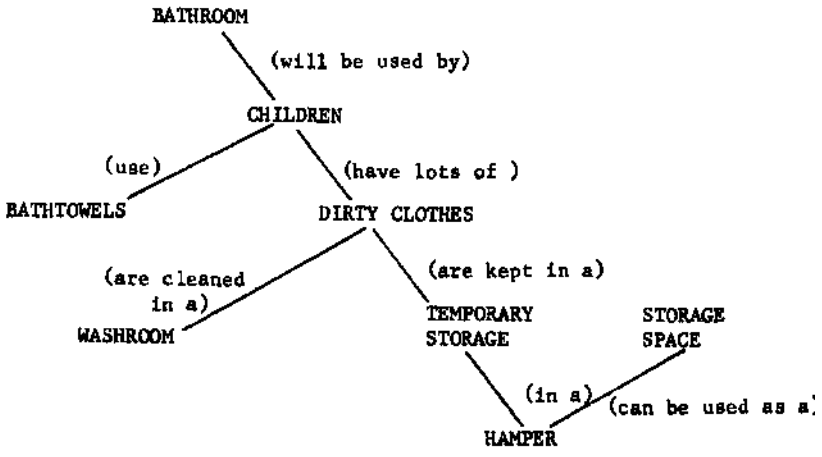



Figure VIa

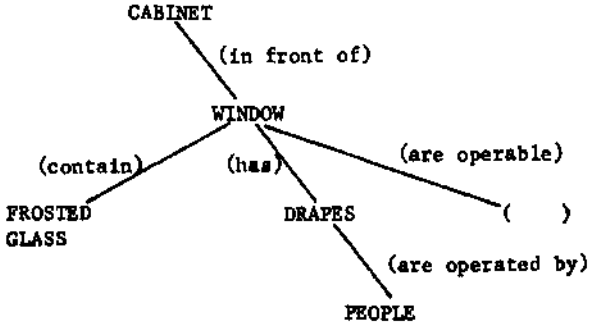



Figure VIb. These two diagrams record the sequential retrieval of information. Time generally is in the direction from top to bottom.

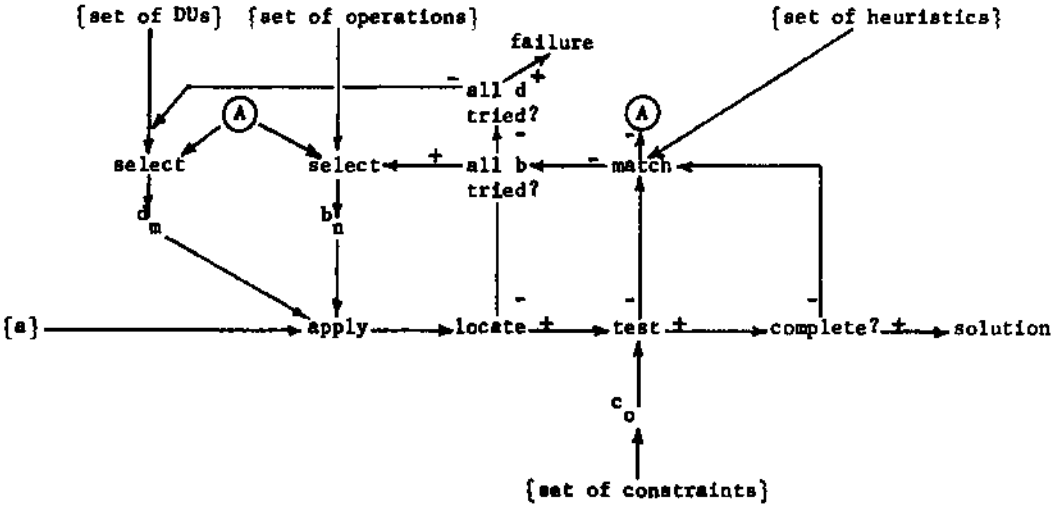



Figure VII. A schematic flowchart of the search aspect of space planning problems.

# Towards Design Theory and expandable rationality : The unfinished program of Herbert Simon.[1]

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**Published in the *Journal of Management and Governance* 5:3-4 2002.**

It is said that Herbert Simon would have described himself as follows : «*I am a monomaniac. What I am a monomaniac about is decision making* ». In spite of its shares of legend and humour, this self-portrait deeply reflects the main logic of Herbert Simon's works. From his early papers on administrative behaviour to his last investigations on thought and learning, Simon kept a same goal : to explain complex and mysterious human behaviour by simple and constrained, yet informed, decision rules. « Bounded rationality » was the name he gave to a research orientation[2] wich rejected the maximizing behaviour assumed by classic economics. But beyond this critical aim, Simon attempted to build an empirically grounded theory of human problem solving. A theory that was intended to settle the foundation stone of « behavioural economics ».

Problem solving also soon became the key entry to what he labeled a « science of the artificial » or a « Science of Design ». This *second program* took growing importance in connection with his own involvement in Artificial intelligence and cognitive psychology. Here one can be grateful to Simon's outstanding shrewdness and insight. Although there is now an increased awareness to innovation and growth processes, still few economists would spontaneously think that a good theory of Design is important for their own discipline.

Yet, Simon's attempts to develope a Design theory remain unfinished. I will discuss in this paper the two central reasons that support this point : i) Simon's always maintained that Design and creativity were special forms of problem solving while it is more likely that Decision making and problem solving are restricted forms of Design ; ii) Simon's limited interest for the construction of social interaction which is a key resource of design processes[3]. This discussion will allow me to introduce a concept of « expandable rationality » as a potential paradigm for design theory. To conclude, I will suggest that, in spite of human agents limitations in problem solving and decision making, economic growth and value creation may result from their expandable design abilities.

## I. From Decision making to Design theory :

[1] I am very grateful to Mie Augier, Nicolai J. Foss, Jetta Frost, Anna Grandori, Siegwart lindenberg, and Margit Osterloh for their comments on an ealier draft.

[2] Simon never thought « bounded rationality » was a theory ; this has been confirmed recently by his interview by Augier ( Augier 2001).

[3] My point of view bears on the results of a research program, both theoretical and empirical on Design. The more technical aspects of this work are still to be published but some results have been presented in several papers and conferences (Hatchuel 2001, Hatchuel and Weil 1998, Hatchuel, Lemasson and Weil 2001a, 2001b )

During the fifties and sixties, most economic researchers accepted the idea that the technical and practical meaning of « rational behaviour » was « optimization », either in its simple form (deterministic), or in its sophisticated one (Expected utility theory). The shift of economic and organization sciences towards a « decision » paradigm has been a complex and varied process. Actually, Operations research, micro-economics, statistical theory were all dependant of the same fundamental model of behaviour : how do we efficiently choose between some set of alternatives ? The impact of this conception was such that it did'nt even appear as a paradigm.

**a) Bounded rationality and the « decision paradigm ».**

We all learned Simon's classical critics of such « substantive rationality » and his seminal view on « bounded rationality ». The latter was a conceptual weapon against the « optimization » school which dominated the decision paradigm. Thus « bounded rationality » was a refutation of all the classic hypotheses of optimal choice : perfect knowledge of alternatives and consequences, perfect preferences between consequences and so on. But if Simon was critical to maximization theories, he persistently understood the concept of rationality through one specific operationalization : an empirically grounded theory of human problem solving.

Simon also proposed to build such theory of decision making and problem solving on a « satisficing » principle. This principle introduces subjectivity, « rules of thumb », heuristics or ad hoc moves as basic decision making processes. *For sure, there can be no universal « satisficing » principle or it would appear as a new form of « optimization ».* And « satisfaction » should be endogeneously defined within the decision process. Consequently, Simon often insisted that facing a problem we simultaneously discuss alternatives, goals, constraints and procedures (time, computational costs…). In his view, Decision making was a natural phenomenon that could be studied by computer simulation, empirical analysis or laboratory experiment. This research program lead him to investigate problem solving by lay men or experts in specific situations like games and puzzles where he tried to understand how they muddle through mazes, messes, and ill-structured problems looking for « satisficing solutions ».

**b) Creativity and design as problem solving**

However, the pure description of human decision making seemed a too narrow program for him and Simon revitalized the distinction between « natural sciences » and « sciences of the artificial» or « Design sciences » (Simon 1969) : « *the former study how is the world and exclude the normative* », the latter are concerned by « *how things ought to be in order to attain goals* ». At multiple occasions he insisted on the importance of Design theory as a main purpose of his work, a theory where all his works on learning, thought, and discovery could converge[4].

How did he approach conceptually a Design process ? Not surprisingly, he investigated Design through the lenses of a decision making and problem solving paradigm. One of its first

[4] Before his death, Herbert Simon had accepted recently the invitation to give a lecture through videoconference, in a conference in Lyon (France) devoted to Design sciences that will take place in March 2002..

systematic approach of the subject appeared in his paper with A. Newell and J.C. Shaw, « *The processes of creative thinking* » (1962). Design was clearly described as a form of creative thinking. A situation where « *the product of thinking has novelty and value,…, the thinking is unconventional,…, the problem was vague and ill defined so part of the task was to formulate the problem itself* » .(reprint in Simon 1979 p.144). The main idea of the paper was that the tree-structured or « branch and bound » heuristics used for the simulation of chess playing or logic proofs were a good proxy of Design processes and creativity. However, in this paper, the authors also recognized that « *we are still far from having all the mechanisms that will be required for a complete theory of creativity : these last pages are necessarily extrapolations and more speculative than the earlier sections* » (p163). In such pages, we find mainly a discussion of « imagery » (or imagination) viewed as a natural process which provides « *a plan to the problem solver at least in the sense of a list of the elements he his dealing with and a list of which of these are related* (p.166)». Hence, imagination was necessary to the creative process but its role was to offer a first list of options that were progressively explored until a satisficing solution appeared (we will come back later to this point).

The same line of argument was maintained in later works. In the « Sciences of the artificial » Simon insists again on the importance of the Sciences of Design and on the fact that a general theory of Design was no more an impossible target. In Chapter 5 and 6 of the book he presents a research agenda towards Design theory where he insists again on the fact that a large part of Design situations can be solved by heuristics belonging to bounded decision making. He also comes back to the question of imagination as a useful entry to ill-defined problems. Yet, an entry that doest'nt change the nature of the heuristics used.

This line of thought had its rationale. Simon was undoubtedly interested by engineering design and Architecture and he was convinced that such design activities presented no major difference with the other types of mental activities he was studying and simulating : « *When we study the process of design we discover that design is problem solving. If you have a basic theory of problem solving then you are well on your way to a theory of Design* ». (Simon 1995).

He also reached the same idea for Scientific discovery. In his paper with D.Kulkarni « *the proces of Scientific discovery : the strategy of experimentation* » (1988 reprint in Simon 1989) he simulated the reasoning of the chemist Hans Krebs during the experiments which lead him to discover the « ornithine's cycle ». The program simulates search procedures where hypotheses are generated and evaluated. After several iterations, a satisficing level of comparative confidence characterizes the discovered effect. Finally, for Simon Design, creativity, discovery (even in Art or Science) were composed of the same repertoire of heuristics that we can find in usual problem solving within a bounded rationality perspective.

Fore sure we owe to Simon a shrewd revitalization of Design, a subject largely neglected by economists. *But, can we consider that Simon reached a consistent Design theory ?* Or, that bounded rationality could encompass Design theory and decision making theory under the same umbrella ? I believe that it is not the case. In this note, I will very briefly give some arguments in favour of the idea that Design theory cannot be restricted to problem solving and that problem solving is only a moment in a design process. I will also suggest, with intuitive means, why substantial steps towards a Design theory require a concept of « expandable rationality » and a principle of collective action. I will conclude this short comment by insisting on the importance of design theory for the economics of innovation and contemporary organization theory.

## II) An approach to Design theory : the limits of a problem solving perspective

In this note, it would be too long to present extensively the formal design theory that I have been developing recently. However, I will introduce some important notions of this approach through simple examples, a method also extensively used by Simon who explained his basic views through popular games : the towers of Hanoï, the chess player, the labyrinth,… In his examples, complexity came from the combinatorial explosion of solutions which defeated any attempt to explore all existing alternatives. In such contexts, satisficing solutions were strongly dependant upon previous expertise (memorised patterns allowing quick recognition) and were obtained through rules-of-thumb choices between promising ways. Now, having in mind all the notions developed by Simon, let us introduce *some differences between problem solving and design theory* by comparing, not games, but simple real life situations. This comparison will help us to introduce the notion of «*expandable rationality* » as a paradigmatic condition of Design theory

### II.1. Going to the pictures or a nice party ?

Two groups of friends living in a big town have to organize their next Saturday evening. Group 1 is discussing of a « good movie » and Group 2 of a « nice party ». With intuitive means and simple observations we can get a first distinction between problem solving theory which is well adapted to the « movie case » and something we can call « Design theory » which captures better the « nice party » case.

- First remark : *we can apply to the « good movie » problem all the classics of bounded rationality*. It is impossible to see all the movies in order to choose the best one (an absurd solution). There may exist competing objectives and tastes. Search strategies are needed. The meaning of « good » is vague and a satisficing criteria will be necessary. Computational costs will interact with the explored solutions : the group will not read all the movie critics or will not phone to all friends that have been recently to the pictures. Knowing strategies are required : do group 1 members trust the judgement of critics or do they discuss it ? Logics of discovery and exploration can also be adopted : like choosing the first movie made by a young an unknown director. Finally, expertise will be a powerful mean to orient the problem : some members of the group may know which movie has been selected or awarded in Cannes, Venice, or Berlin and will consider these facts as efficient « cues » (Simon 1996).

- Second remark : Exactly the same set of problem solving procedures will be required in the Group 2 for the « nice party » case. Yet, and this is our crucial point, « party » is an infinitely expandable concept and *different processes will also appear in group 2*. Let us discuss three of them : the unexpected expansions of the initial concepts, the design of learning devices, social interaction as a design resource.

#### a) The unexpected expansions of the initial concepts :

When Group 1 ends his work a movie has been selected. Moreover, during the discussions and procedures the understanding of what is «a movie we can see in a theater downtown next saturday » will remain unchanged. Yet, in spite of this stability, case 1 requires all the problem solving procedures that have been described by Simon as models of « bounded rationality ». But, in case 2, there is something more : *unexpected designs of what is a « party »*

*can emerge from the process* ! This is only a possible outcome also recognized by Simon when he approached « creativity » (Simon, Newell and, Shaw 1962). But what makes such emergence possible ? Exploring this question helps to distinguish Design activity from problem solving through some crucial aspects :

- having to organize a « nice party » would appear in Simon's terms as a vague, and ill-structured problem. He would suggest that the first step is to define the problem space, to « *form »* it. From the point of view of design theory, the *project* of a « nice party » can be described in quite opposite words : *it is a semantically clear and well formulated departure point.* In Simon's language it appears as some vague agenda or goal setting, but such notions miss the specificities of the formulation[5]. By being apparently vague and ill-structured, the concept of « nice party » allows either for conformity to usual party standards or for innovative suggestions. Constraints (cost, time, location…) will be investigated and selected but their composition and impact on the design work is not deterministic. There is nothing one can call « the problem » or « the set of constraints ». There is *a project* ( a more adequate designation than « problem »*)* to handle and there is no mechanistic relation between this project and the undefined number of « problems » that the design work will meet.

- This explains why some so-called design problems are not real design projects. If a machine is well defined by a set of organs and control parameters, a lot of modifications of such machine can be treated by problem solving procedures. We face a real design project only if the formulation of the initial concepts allows for unexpected expansion. The economic litterature has often described the notion of a « dominant design » in some sectors : in such cases, new products projects are under so many constraints that they tend to disappear, until some innovative player appears.

- Design projects are not necessarily creative. But creativity needs a design logic in the approach of a project (e.g. concepts allowing surprising expansion). To capture creativity Simon introduced « imagination » within a problem solving approach. He thought that the task of imagination was to provide the first list of actions, and that the rest of the process was problem solving heuristics. There are several difficulties raised by such approach. The first one, is that « imagination » appears as an exogeneous entry to the design process and not as something that can be triggered by designable procedures. The second difficulty is that imagination (as defined by Simon) can appear *everywhere* in the process, at early or late phases. For example in case 2, its is always possible to add new events or facets to a party even during the party itself. And these events can actually change the perception of the party. To avoid these difficulties, a more thorough analysis of what we call « imagination » is needed, otherwise one could claim that the concept encompasses all the process and dismantles the value of problem solving heuristics as a grounded theory.

What are the consequences of these remarks ? If, unexpected expansions of the initial concepts are integral to a design process, hence a design situation is not a special case of problem solving. A « feline » is not a special case of « cat », but the reverse proposition is true. Design theory contains problem solving theory because any design process can use all problem solving procedures. Moreover, the unexpected expansions of the initial concept controls the generation of problems, and these will or will not be solved. Hence, Design theory is not only

[5] This kind of short sentence containing rich semantic possibilities often serves to organize design competitions. In design practice they are often called « briefs », a label well adapted to the laconic description of the project.

problem forming or solving, it has to capture the process of conceptual expansions. A key aspect of this process is the design of « learning devices ».

**b)The design of learning devices** :

At the end of case 1 (the movie case), some learning is observable. The films that one can see dowtown are better known ; some critics have been read ; new movie theaters may have been discovered. The expertise of all participants has increased. The same learnings occur in group 2. Yet, other learning paths appear again. In case 1, learning is caused by the exploration of already recognized knowing areas : films, theaters, comedians, members preferences... While in case 2, it has no such predetermined structure. Somebody could suggest a fancy party or to organize the party on cruise. In each case, the learning process will focus on unpredictable areas. Hence, in case 2, learning determines the generation of problems and has to be considered as a design area i.e. as a process designed to generate new concepts and problems. We call « learning devices » such processes because they are more than means to test solutions. They are designed *to learn about what has to be learned or could be learned :*.a drawing, a mock-up, a prototype, a scientific experimental model, a rehearsal are usual « learning devices »[6]. Simon's 1988 paper (Simon and kulkarni 1988) contains an excellent example of learning device. In this paper, the authors attempt to simulate the discovery logic of a great biologist Hans Krebs. One of their conclusions was that « *The tissue culture method acquired here was his secret weapon, his source of comparative advantage* » (p.381). Krebs had adapted for his own purposes the « tissue culture » method (for experimentation and observation) that was developed by another scientist and this method opened the learning path that reached the ornithine discovery. In this case, the main design action was the innovative reuse of an experimental model or, in our terms, of a crucial learning device. Undoubtedly, this paper is one of the *richest modelling of problem generation and solving.* Yet, the model focused exclusively on the experimental tactics of Krebs, once selected the « tissue culture » method[7]. Anyway, designing the appropriate learning devices is a central aspect of a design process as search procedures are dependent from the properties of such devices.

**c) Social interaction as a design resource and a designable area** :

Between case 1 and case 2, there is a third significant difference. *The decision makers of group 1 are also the « clients » of their own choices*. In case 2, this is no more true : group 2 have at least to take into account the expected judgements and behaviour of the selected guests. This means that the success of the party cannot be completely controlled by the designers. This is also a common aspect of decision-making in organizations (Hatchuel and Molet 1986). For sure, existing knowledge about the clients can impact the satisficing process. Even a computerized chess player could adapt his strategy by learning from the moves of his human opponent. But we should not *forget that understanding and designing the social interactions of a design process is an essential part of the design process itself*. Let us come back to case 2, the guests can be perceived as a resource of the design process : some of them, if previously informed, could organize surprising events ; they could also help for drinks and meal preparation and so on. *The social interaction becomes both a resource and a designable area*. This is an obvious aspect of the design of services and an essential element for the understanding of design worlds (Hatchuel 2001) like architecture or Art. It also captures the empirical fact that design is dependant of the information and education required from the « client » (Suh 1988). Thus, Design theory is both *an output and a resource* of social

[6] In the case of nice party one can think of some forms of rehearsals or some preparatory drawings.
[7] This can be explained by the complexity to simulate the generation and comparison of distinct learning devices

interaction : this is obvious in Art and it is universally true. (Hatchuel 2001). Considering social interaction as a designable area is a key feature for economic and organization theory as it directly implies that value creation and creativity are dependant of organizational forms and of the social interactions that shape economic transactions.[8]

These three differences can be considered as a partial agenda for an extension of problem solving theory towards Design theory. In chapter 5 of « the Sciences of the Artificial », Simon was not far from a similar research agenda. Nevertheless, he also insisted on the idea that Design theory would need *no new theoretical langage i.e. no new modelling logic*. Later, he gave several indications of his good recognition of the requisits of a research program on design : « *Today's expert system make use of problem representations that already exist. But major advances in human knowledge frequently derive from New ways of thinking about problems »* (Simon 1986). However, a thorough examination of these texts (too long to undertake here) shows that all his arguments aimed to avoid any substantial difference with problem solving theory. There is no room here to discuss in detail this position. Let us mention that the departure point of our work was quite opposite to Simon's one : we think that design theory requires different conceptual instruments than problem solving. And, using the same examples I will briefly introduce a theoretical discussion on concepts and a principle of « expandable rationality » (Hatchuel 2001) that could help the reader to understand why Simon's position was perhaps too restrictive.

### II.2. Concepts and non-countable sets : a definition of « expandable rationality »

A basic procedure of problem solving is the generation of a short list of possible solutions that could be evaluated and compared. In case1, the set of all solutions (all the movies presented in the town) is clearly a *countable* set (a list of solutions may be infinite but countable), a classic concept in standard Set theory. Consequently, the short list appears as an extraction from the existing list of films.

In case 2, we face a different landscape. The set of all possible « parties » is a *non-countable* one if we refer to the definition of non countable sets in Set theory. Why is it so ? Intuitively : the number of parameters defining a « party » can be made infinite (let us only assume that the party contains some games or shows and infinity is there). But, more technically, we can also mimic the constructive proof of the non countability of Real numbers in Set theory : if one assumes that there exists a countable set of possible « parties », it will always be possible to create new parties by combination of the listed ones and so on…(an important argument here is that two concepts of a « party » can always be merged in a new concept of party, infinitely).

Now, these abstract propositions have two important consequences.

**- *Bounded rationality revisited*** : what means « exploring » an infinite and non-countable set ? What means an exhaustive listing of the real numbers ? Our limits are no more caused by human, cognitive or computational bounds. We have to accept that the issue *has no*

[8] The literature on organizational learning and knowledge creating firms also insists on the importance of social interactions in knowledge creation. However, most often there is no contingency theory that links the content of knowledge produced to the shape and logic of the social interaction. It is one of the advantages of design theory to offer such contingency views : Planes and cars are complex technical systems, their design needs complex social interactions but not the same ones (for a discussion of the literature on this point see Hatchuel and Weil 1998, Hatchuel, lemasson, weil 2001).

*theoretical sense*. Even a theoretical exploration method having infinite time and resources would fail. Hence, it is the basic concept of « exploring » a space of possiblities that we have to abandon. Like almost all common nouns, the word « party » is undefinable as a closed list of objects. In case 1, « films » form a countable set only because the inquiry was restricted to « films that can be seen in dowtown theaters on Saturday ». These specific «films » have been made countable *by previous designs and previous social conventions*. Hence, Group 1 has no design work to do but they have a problem to solve. In real design processes, we have to manipulate concepts which correspond to non-countable sets. Therefore, there is no way to extract lists of solutions from previous lists of solutions. The only approach left is to *expand* the initial concept by adding usual or innovative qualifying properties. Exactly in the same way that we define subsets of the Reals by adding properties and not by selecting numbers from a list. Practically, group 2 will probably begin by formulating different contrasting « stories » of nice parties ; these stories will be discussed and reworked in order to progressively reach a « grammar » of attracting nice parties. Then learning devices will be settled (call to friends, contacts with suppliers…). They will bring new knowledge and new concept of parties and the expansion process will begin.

***- A concept of « expandable rationality »*** : Non countable sets are infinitely expandable. So, the concept of a « party » is also infinitely expandable while the concept of the « movies that we can see downtown » is not. This conveys a new perspective on rationality : *what means rational behaviour in infinitely expandable and non countable sets of actions* ? We will not attempt here a technical definition of such behaviour ; but, there is at least one property that one expects from a consistent rationality concept in such context : *to be expandable.* A first characteristic of such rationality is *our ability to manipulate (individually and collectively) infinitely expandable concepts*. A capacity that is a necessary condition for any Design process and that we consider as a *potential paradigm* for economics of innovation and organization theory (Hatchuel 2001). In classic combinatorial problems, like in chess playing, there is no real design project, and we have no other choice than to adopt models of bounded rationality. However, creativity is still possible when the space of strategies seems infinitely expandable to the players [9]. This probably means that very innovative players think like designers. In a fascinating paper on chess skill, entitled «*The mind's eye in chess* » (Simon and Chase 1973) Simon tried to capture Chess skill. In this paper Simon recognizes the existence of « a perceptual structure » which captures long term memory and practice, and also allows the recognition and generation of innovative patterns. In our terms, this means that such perceptual structures are not lists of previous games, but *expandable concepts* about games. These concepts can be innovatively expanded by highly skilled and trained players. In this paper, Simon is obviously facing a new perspective : « *hence, the overriding factor in chess skill is practice…and the same is true of any skilled task (e.g. football, music)* ». A perspective rather far from problem solving heuristics.

## III. Concluding remarks and Openings : Design theory, economics and organization theory

Simon was one the very few authors of the last century (at least in social and and psychological research.) to understand the theoretical importance of Design (in engineering, architecture or elsewhere). He also called for the elaboration of a design theory. Nevertheless, he thought that we already had all the theoretical instruments required for such endeavour and

[9] This is only how it appears to us, but in reality it is not infinitely expandable as it is a finite and countable set.

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that they could be found in the models he developed to simulate complex problem solving in bounded rationality contexts. One can doubt that this was a valid position. Our concept of expandable rationality brings us within the problems of the continuum hypothesis and not in the world of discrete mathematics which is the necessary realm of computers. This is at least a piece of evidence in favour of our doubts.

But why Design theory matters for economics or organization theory ? *And why should researchers in these fields bother with Simon's models of thought, or more modestly with the discussion on the frontiers between problem solving and Design theory that we offered here ?* I will follow here the same line of argument than Grandori's view about the importance of a logic of discovery in governance forms (Grandori 2001) ?

We all know that growth is not only the consequence of cost reduction through competition. Innovation, be it technical, esthetical or organizational, is a major process for the expansion of wealth. Simon tried to prove that we could capture complex problem solving, even creativity, in terms of simple heuristics and satisficing criteria. This position was an extremely fruitful critic of the « optimizing » school. Yet, it did'nt capture and explain *the expansion of goods, wealth and values in advanced contemporary economies* and how collective action within firms and between firms and clients could create a so huge number of concepts, values, and objects (for better or worse). The idea of Bounded rationality seems to diminish the computational abilities of economic agents. They deal with uncertainties and complexity with the limited help of rules of the thumb principles. They use short list of actions instead of rich spaces of possibilities. They suffer from cognitive and practical limitations. All this has been perfectly taught to us by Simon. But from these ideas, considered as basics of the program of « behavioural economics » that Simon called for (Mie Augier 2001), one could conclude that the efficency of economies and organizations is necessarily *hindered* by our problem solving limitations. Then, why do we observe Growth and wealth ? There one can see the theoretical importance of distinguishing between Design and problem solving.

*Our main hypothesis is that human agents are limited decision makers but « good » natural designers (including social interaction as a design area).* This hypothesis fits well with all what we learned from Simon and avoids some of its consequences. Human agents have a surprising and infinitely expandable ability to create stories, forms, and concepts. Thus even if good design also needs problem solving procedures, at least it can compensate their weaknesses. Moreover, our design ability can be improved at least through the three crucial processes we evoked :

- *improving concept expandability* : learning to manipulate concepts that correspond to non countable sets or perceptual structures (Simon and Chase 1973 : in some way all schools of Art try to do that).
- *Designing new learning devices* : New prototyping, virtual mock-ups, video aided rehearsals, cooperation aiding software…
- *Looking for new forms of social interaction in design* : for example, involving users or other stakeholders in the design process.

However, economic agents and economic theory still look at human agents as « decision makers ». Most often agents cannot recognize their design capabilities because they have no design theory to mirror their own thinking. This also explains why classic organizational or market failures are not so important for growth. Imperfect competition or agency behaviour are major problems within a decision paradigm. Yet, within a paradigm of

expandable rationality these failures become acceptable if they do not inhibit the value creation process. A very unefficient company in terms of cost control could create much more profit and social wealth than a well controlled one if the former has a better design process than the latter.

So, new theoretical questions appear. What makes that a company has a better design process than an other ? What are the consequences of design theory on organization theory ? What are the consequences of expandable rationality in terms of organizational principles and processes ? As these questions have been developed in other papers (Hatchuel and Weil 1998, Hatchuel, Lemasson and Weil 2001a, 2001b ), I will conclude this note by brief comments on the two examples.

Let us imagine that group 1 and group 2 are not groups of friends but small companies. Group 1 wants to offer a new service : assistance to movie information and selection while group 2 offers to design and organize « nice parties » for ordering clients. Obviously, group 2 and group 1 will not adopt the same organization and the same type of prices and their relation to clients will be very different. Yet, both are service companies, so where are the driving forces behind different structures and governance forms ? The answer is in the design procedures of these two services. Group 1 will offer problem solving procedures (e.g. Web sites, journals, data banks, critics, chat rooms, clients judgements about movies) while group 2 will propose design assistance (team working, consultancy, artists, experts plus all the same devices offered by group 1). The economic literature has recognized the specific properties of such services. Both need interaction between the producer and consumer (this is obvious in group 2 and group 1 can ask clients to feed the system with their evaluations). They also require mutual trust as the quality of such services cannot be easily assessed by the consumer. However due to the contrasted design processes of these goods, interaction and trust will not be similarly shaped or related to the same contents in both cases. In case 2, the interactions can take place during all the design of the party and even during it. While, group 1, will rarely offer more than information, debates and meetings with film makers and comedians. This indicates how a good design theory is a necessary ground for Economic theory and organization theory.

Herbert Simon opened the way towards a major improvement in the economic and social sciences. Not only by criticizing perfect choice theory, but also by understanding the necessity to build Design as a Science and a theory. However, he was convinced that Design and creativity was just a special case of problem solving. If there is no doubt that problem solving is part of a design process, yet it is not the whole process. Simon's identification of design theory to problem solving theory may have also limited the awareness of economists and organization theorists to the implications of human capacities in design for a theory of wealth and growth. If design is mere problem solving so why should we give to such activity any specific theoretical place ?

Thus, one could not reduce the importance of Simon's outstanding scientific contribution by considering that his attempts to build a design theory remain unfinished. Research goes on. And we hope that this short note, while reflecting our debt to Herbert Simon'second program, also has some flavour of progress.

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The 1975 ACM Turing Award was presented jointly to Allen Newell and Herbert A. Simon at the ACM Annual Conference in Minneapolis, October 20. In introducing the recipients, Bernard A. Galler, Chairman of the Turing Award Committee, read the following citation:

"It is a privilege to be able to present the ACM Turing Award to two friends of long standing, Professors Allen Newell and Herbert A. Simon, both of Carnegie-Mellon University.

"In joint scientific efforts extending over twenty years, initially in collaboration with J.C. Shaw at the RAND Corporation, and subsequently with numerous faculty and student colleagues at Carnegie-Mellon University, they have made basic contributions to artificial intelligence, the psychology of human cognition, and list processing.

"In artificial intelligence, they contributed to the establishment of the field as an area of scientific endeavor, to the development of heuristic programming generally, and of heuristic search, means-ends analysis, and methods of induction, in particular; providing demonstrations of the sufficiency of these mechanisms to solve interesting problems.

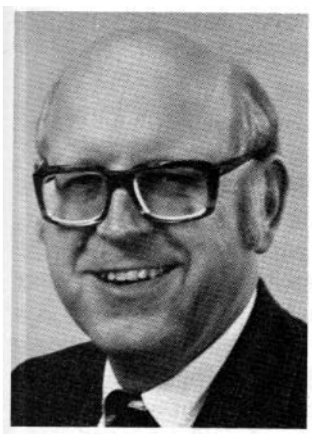
"In psychology, they were principal instigators of the idea that human cognition can be described in terms of a symbol system, and they have developed detailed theories for human problem solving, verbal learning and inductive behavior in a number of task domains, using computer programs embodying these theories to simulate the human behavior.

"They were apparently the inventors of list processing, and have been major contributors to both software technology and the development of the concept of the computer as a system of manipulating symbolic structures and not just as a processor of numerical data.

"It is an honor for Professors Newell and Simon to be given this award, but it is also an honor for ACM to be able to add their names to our list of recipients, since by their presence, they will add to the prestige and importance of the ACM Turing Award."

# Computer Science as Empirical Inquiry: Symbols and Search

Allen Newell and Herbert A. Simon



Computer science is the study of the phenomena surrounding computers. The founders of this society understood this very well when they called themselves the Association for Computing Machinery. The machine—not just the hardware, but the programmed, living machine—is the organism we study.

This is the tenth Turing Lecture. The nine persons who preceded us on this platform have presented nine different views of computer science. For our organism, the machine, can be studied at many levels and from many sides. We are deeply honored to appear here today and to present yet another view, the one that has permeated the scientific work for which we have been

Key Words and Phrases: symbols, search, science, computer science, empirical, Turing, artificial intelligence, intelligence, list processing, cognition, heuristics, problem solving.

CR Categories: 1.0, 2.1, 3.3, 3.6, 5.7.



The authors' research over the years has been supported in part by the Advanced Research Projects Agency of the Department of Defense (monitored by the Air Force Office of Scientific Research) and in part by the National Institutes of Mental Health.

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cited. We wish to speak of computer science as empirical inquiry.

Our view is only one of many; the previous lectures make that clear. However, even taken together the lectures fail to cover the whole scope of our science. Many fundamental aspects of it have not been represented in these ten awards. And if the time ever arrives, surely not soon, when the compass has been boxed, when computer science has been discussed from every side, it will be time to start the cycle again. For the hare as lecturer will have to make an annual sprint to overtake the cumulation of small, incremental gains that the tortoise of scientific and technical development has achieved in his steady march. Each year will create a new gap and call for a new sprint, for in science there is no final word.

Computer science is an empirical discipline. We would have called it an experimental science, but like astronomy, economics, and geology, some of its unique forms of observation and experience do not fit a narrow stereotype of the experimental method. None the less, they are experiments. Each new machine that is built is an experiment. Actually constructing the machine poses a question to nature; and we listen for the answer by observing the machine in operation and analyzing it by all analytical and measurement means available. Each new program that is built is an expermient. It poses a question to nature, and its behavior offers clues to an answer. Neither machines nor programs are black boxes; they are artifacts that have been designed, both hardware and software, and we can open them up and look inside. We can relate their structure to their behavior and draw many lessons from a single experiment. We don't have to build 100 copies of, say, a theorem prover, to demonstrate statistically that it has not overcome the combinatorial explosion of search in the way hoped for. Inspection of the program in the light of a few runs reveals the flaw and lets us proceed to the next attempt.

We build computers and programs for many reasons. We build them to serve society and as tools for carrying out the economic tasks of society. But as basic scientists we build machines and programs as a way of discovering new phenomena and analyzing phenomena we already know about. Society often becomes confused about this, believing that computers and programs are to be constructed only for the economic use that can be made of them (or as intermediate items in a developmental sequence leading to such use). It needs to understand that the phenomena surrounding computers are deep and obscure, requiring much experimentation to assess their nature. It needs to understand that, as in any science, the gains that accrue from such experimentation and understanding pay off in the permanent acquisition of new techniques; and that it is these techniques that will create the instruments to help society in achieving its goals.

Our purpose here, however, is not to plead for understanding from an outside world. It is to examine one aspect of our science, the development of new basic understanding by empirical inquiry. This is best done by illustrations. We will be pardoned if, presuming upon the occasion, we choose our examples from the area of our own research. As will become apparent, these examples involve the whole development of artificial intelligence, especially in its early years. They rest on much more than our own personal contributions. And even where we have made direct contributions, this has been done in cooperation with others. Our collaborators have included especially Cliff Shaw, with whom we formed a team of three through the exciting period of the late fifties. But we have also worked with a great many colleagues and students at Carnegie-Mellon University.

Time permits taking up just two examples. The first is the development of the notion of a symbolic system. The second is the development of the notion of heuristic search. Both conceptions have deep significance for understanding how information is processed and how intelligence is achieved. However, they do not come close to exhausting the full scope of artificial intelligence, though they seem to us to be useful for exhibiting the nature of fundamental knowledge in this part of computer science.

## I. Symbols and Physical Symbol Systems

One of the fundamental contributions to knowledge of computer science has been to explain, at a rather basic level, what symbols are. This explanation is a scientific proposition about Nature. It is empirically derived, with a long and gradual development.

Symbols lie at the root of intelligent action, which is, of course, the primary topic of artificial intelligence. For that matter, it is a primary question for all of computer science. For all information is processed by computers in the service of ends, and we measure the intelligence of a system by its ability to achieve stated ends in the face of variations, difficulties and complexities posed by the task environment. This general investment of computer science in attaining intelligence is obscured when the tasks being accomplished are

limited in scope, for then the full variations in the environment can be accurately foreseen. It becomes more obvious as we extend computers to more global, complex and knowledge-intensive tasks—as we attempt to make them our agents, capable of handling on their own the full contingencies of the natural world.

Our understanding of the systems requirements for intelligent action emerges slowly. It is composite, for no single elementary thing accounts for intelligence in all its manifestations. There is no "intelligence principle," just as there is no "vital principle" that conveys by its very nature the essence of life. But the lack of a simple *deus ex machina* does not imply that there are no structural requirements for intelligence. One such requirement is the ability to store and manipulate symbols. To put the scientific question, we may paraphrase the title of a famous paper by Warren McCulloch [1961]: What is a symbol, that intelligence may use it, and intelligence, that it may use a symbol?

### Laws of Qualitative Structure

All sciences characterize the essential nature of the systems they study. These characterizations are invariably qualitative in nature, for they set the terms within which more detailed knowledge can be developed. Their essence can often be captured in very short, very general statements. One might judge these general laws, due to their limited specificity, as making relatively little contribution to the sum of a science, were it not for the historical evidence that shows them to be results of the greatest importance.

**The Cell Doctrine in Biology.** A good example of a law of qualitative structure is the cell doctrine in biology, which states that the basic building block of all living organisms is the cell. Cells come in a large variety of forms, though they all have a nucleus surrounded by protoplasm, the whole encased by a membrane. But this internal structure was not, historically, part of the specification of the cell doctrine; it was subsequent specificity developed by intensive investigation. The cell doctrine can be conveyed almost entirely by the statement we gave above, along with some vague notions about what size a cell can be. The impact of this law on biology, however, has been tremendous, and the lost motion in the field prior to its gradual acceptance was considerable.

**Plate Tectonics in Geology.** Geology provides an interesting example of a qualitative structure law, interesting because it has gained acceptance in the last decade and so its rise in status is still fresh in memory. The theory of plate tectonics asserts that the surface of the globe is a collection of huge plates—a few dozen in all—which move (at geological speeds) against, over, and under each other into the center of the earth, where they lose their identity. The movements of the plates account for the shapes and relative locations of the continents and oceans, for the areas of volcanic and earthquake activity, for the deep sea ridges, and so on. With a few additional particulars as to speed and size, the essential theory has been specified. It was of course not accepted until it succeeded in explaining a number of details, all of which hung together (e.g. accounting for flora, fauna, and stratification agreements between West Africa and Northeast South America). The plate tectonics theory is highly qualitative. Now that it is accepted, the whole earth seems to offer evidence for it everywhere, for we see the world in its terms.

**The Germ Theory of Disease.** It is little more than a century since Pasteur enunciated the germ theory of disease, a law of qualitative structure that produced a revolution in medicine. The theory proposes that most diseases are caused by the presence and multiplication in the body of tiny single-celled living organisms, and that contagion consists in the transmission of these organisms from one host to another. A large part of the elaboration of the theory consisted in identifying the organisms associated with specific diseases, describing them, and tracing their life histories. The fact that the law has many exceptions—that many diseases are not produced by germs—does not detract from its importance. The law tells us to look for a particular kind of cause; it does not insist that we will always find it.

**The Doctrine of Atomism.** The doctrine of atomism offers an interesting contrast to the three laws of qualitative structure we have just described. As it emerged from the work of Dalton and his demonstrations that the chemicals combined in fixed proportions, the law provided a typical example of qualitative structure: the elements are composed of small, uniform particles, differing from one element to another. But because the underlying species of atoms are so simple and limited in their variety, quantitative theories were soon formulated which assimilated all the general structure in the original qualitative hypothesis. With cells, tectonic plates, and germs, the variety of structure is so great that the underlying qualitative principle remains distinct, and its contribution to the total theory clearly discernible.

**Conclusion.** Laws of qualitative structure are seen everywhere in science. Some of our greatest scientific discoveries are to be found among them. As the examples illustrate, they often set the terms on which a whole science operates.

### Physical Symbol Systems

Let us return to the topic of symbols, and define a *physical symbol system*. The adjective "physical" denotes two important features: (1) Such systems clearly obey the laws of physics—they are realizable by engineered systems made of engineered components; (2) although our use of the term "symbol" prefigures our intended interpretation, it is not restricted to human symbol systems.

A physical symbol system consists of a set of entities, called symbols, which are physical patterns that can occur as components of another type of entity called an expression (or symbol structure). Thus, a symbol structure is composed of a number of instances (or tokens) of symbols related in some physical way (such as one token being next to another). At any instant of time the system will contain a collection of these symbol structures. Besides these structures, the system also contains a collection of processes that operate on expressions to produce other expressions: processes of creation, modification, reproduction and destruction. A physical symbol system is a machine that produces through time an evolving collection of symbol structures. Such a system exists in a world of objects wider than just these symbolic expressions themselves.

Two notions are central to this structure of expressions, symbols, and objects: designation and interpretation.

> *Designation.* An expression designates an object if, given the expression, the system can either affect the object itself or behave in ways dependent on the object.

In either case, access to the object via the expression has been obtained, which is the essence of designation.

> *Interpretation.* The system can interpret an expression if the expression designates a process and if, given the expression, the system can carry out the process.

Interpretation implies a special form of dependent action: given an expression the system can perform the indicated process, which is to say, it can evoke and execute its own processes from expressions that designate them.

A system capable of designation and interpretation, in the sense just indicated, must also meet a number of additional requirements, of completeness and closure. We will have space only to mention these briefly; all of them are important and have far-reaching consequences.

(1) A symbol may be used to designate any expression whatsoever. That is, given a symbol, it is not prescribed a priori what expressions it can designate. This arbitrariness pertains only to symbols; the symbol tokens and their mutual relations determine what object is designated by a complex expression. (2) There exist expressions that designate every process of which the machine is capable. (3) There exist processes for creating any expression and for modifying any expression in arbitrary ways. (4) Expressions are stable; once created they will continue to exist until explicitly modified or deleted. (5) The number of expressions that the system can hold is essentially unbounded.

The type of system we have just defined is not unfamiliar to computer scientists. It bears a strong family resemblance to all general purpose computers. If a symbol manipulation language, such as LISP, is taken as defining a machine, then the kinship becomes truly brotherly. Our intent in laying out such a system is not to propose something new. Just the opposite: it is to show what is now known and hypothesized about systems that satisfy such a characterization.

We can now state a general scientific hypothesis—a law of qualitative structure for symbol systems:

> *The Physical Symbol System Hypothesis.* A physical symbol system has the necessary and sufficient means for general intelligent action.

By "necessary" we mean that any system that exhibits general intelligence will prove upon analysis to be a physical symbol system. By "sufficient" we mean that any physical symbol system of sufficient size can be organized further to exhibit general intelligence. By "general intelligent action" we wish to indicate the same scope of intelligence as we see in humian action: that in any real situation behavior approprate to the ends of the system and adaptive to the demands of the environment can occur, within some limits of speed and complexity.

The Physical Symbol System Hypothesis clearly is a law of qualitative structure. It specifies a general class of systems within which one will find those capable of intelligent action.

This is an empirical hypothesis. We have defined a class of systems; we wish to ask whether that class accounts for a set of phenomena we find in the real world. Intelligent action is everywhere around us in the biological world, mostly in human behavior. It is a form of behavior we can recognize by its effects whether it is performed by humans or not. The hypothesis could indeed be false. Intelligent behavior is not so easy to produce that any system will exhibit it willy-nilly. Indeed, there are people whose analyses lead them to conclude either on philosophical or on scientific grounds that the hypothesis *is* false. Scientifically, one

can attack or defend it only by bringing forth empirical evidence about the natural world.

We now need to trace the development of this hypothesis and look at the evidence for it.

### Development of the Symbol System Hypothesis

A physical symbol system is an instance of a universal machine. Thus the symbol system hypothesis implies that intelligence will be realized by a universal computer. However, the hypothesis goes far beyond the argument, often made on general grounds of physical determinism, that any computation that is realizable can be realized by a universal machine, provided that it is specified. For it asserts specifically that the intelligent machine is a symbol system, thus making a specific architectural assertion about the nature of intelligent systems. It is important to understand how this additional specificity arose.

**Formal Logic.** The roots of the hypothesis go back to the program of Frege and of Whitehead and Russell for formalizing logic: capturing the basic conceptual notions of mathematics in logic and putting the notions of proof and deduction on a secure footing. This effort culminated in mathematical logic—our familiar propositional, first-order, and higher-order logics. It developed a characteristic view, often referred to as the "symbol game." Logic, and by incorporation all of mathematics, was a game played with meaningless tokens according to certain purely syntactic rules. All meaning had been purged. One had a mechanical, though permissive (we would now say nondeterministic), system about which various things could be proved. Thus progress was first made by walking away from all that seemed relevant to meaning and human symbols. We could call this the stage of formal symbol manipulation.

This general attitude is well reflected in the development of information theory. It was pointed out time and again that Shannon had defined a system that was useful only for communication and selection, and which had nothing to do with meaning. Regrets were expressed that such a general name as "information theory" had been given to the field, and attempts were made to rechristen it as "the theory of selective information"—to no avail, of course.

**Turing Machines and the Digital Computer.** The development of the first digital computers and of automata theory, starting with Turing's own work in the '30s, can be treated together. They agree in their view of what is essential. Let us use Turing's own model, for it shows the features well.

A Turing machine consists of two memories: an unbounded tape and a finite state control. The tape holds data, i.e. the famous zeroes and ones. The machine has a very small set of proper operations—read, write, and scan operations—on the tape. The read operation is not a data operation, but provides conditional branching to a control state as a function of the data under the read head. As we all know, this model contains the essentials of all computers, in terms of what they can do, though other computers with different memories and operations might carry out the same computations with different requirements of space and time. In particular, the model of a Turing machine contains within it the notions both of what cannot be computed and of universal machines—computers that can do anything that can be done by any machine.

We should marvel that two of our deepest insights into information processing were achieved in the thirties, before modern computers came into being. It is a tribute to the genius of Alan Turing. It is also a tribute to the development of mathematical logic at the time, and testimony to the depth of computer science's obligation to it. Concurrently with Turing's work appeared the work of the logicians Emil Post and (independently) Alonzo Church. Starting from independent notions of logistic systems (Post productions and recursive functions, respectively) they arrived at analogous results on undecidability and universality—results that were soon shown to imply that all three systems were equivalent. Indeed, the convergence of all these attempts to define the most general class of information processing systems provides some of the force of our conviction that we have captured the essentials of information processing in these models.

In none of these systems is there, on the surface, a concept of the symbol as something that *designates*. The data are regarded as just strings of zeroes and ones—indeed that data be inert is essential to the reduction of computation to physical process. The finite state control system was always viewed as a small controller, and logical games were played to see how small a state system could be used without destroying the universality of the machine. No games, as far as we can tell, were ever played to add new states dynamically to the finite control—to think of the control memory as holding the bulk of the system's knowledge. What was accomplished at this stage was half the principle of interpretation—showing that a machine could be run from a description. Thus, this is the stage of automatic formal symbol manipulation.

**The Stored Program Concept.** With the development of the second generation of electronic machines in the mid-forties (after the Eniac) came the stored program concept. This was rightfully hailed as a milestone, both conceptually and practically. Programs now can be data, and can be operated on as data. This capability is, of course, already implicit in the model of Turing: the descriptions are on the very same tape as the data. Yet the idea was realized only when machines acquired enough memory to make it practicable to locate actual programs in some internal place. After all, the Eniac had only twenty registers.

The stored program concept embodies the second

half of the interpretation principle, the part that says that the system's own data can be interpreted. But it does not yet contain the notion of designation—of the physical relation that underlies meaning.

**List Processing.** The next step, taken in 1956, was list processing. The contents of the data structures were now symbols, in the sense of our physical symbol system: patterns that designated, that had referents. Lists held addresses which permitted access to other lists—thus the notion of list structures. That this was a new view was demonstrated to us many times in the early days of list processing when colleagues would ask where the data were—that is, which list finally held the collections of bits that were the content of the system. They found it strange that there were no such bits, there were only symbols that designated yet other symbol structures.

List processing is simultaneously three things in the development of computer science. (1) It is the creation of a genuine dynamic memory structure in a machine that had heretofore been perceived as having fixed structure. It added to our ensemble of operations those that built and modified structure in addition to those that replaced and changed content. (2) It was an early demonstration of the basic abstraction that a computer consists of a set of data types and a set of operations proper to these data types, so that a computational system should employ whatever data types are appropriate to the application, independent of the underlying machine. (3) List processing produced a model of designation, thus defining symbol manipulation in the sense in which we use this concept in computer science today.

As often occurs, the practice of the time already anticipated all the elements of list processing: addresses are obviously used to gain access, the drum machines used linked programs (so called one-plus-one addressing), and so on. But the conception of list processing as an abstraction created a new world in which designation and dynamic symbolic structure were the defining characteristics. The embedding of the early list processing systems in languages (the IPLs, LISP) is often decried as having been a barrier to the diffusion of list processing techniques throughout programming practice; but it was the vehicle that held the abstraction together.

**LISP.** One more step is worth noting: McCarthy's creation of LISP in 1959–60 [McCarthy, 1960]. It completed the act of abstraction, lifting list structures out of their embedding in concrete machines, creating a new formal system with S-expressions, which could be shown to be equivalent to the other universal schemes of computation.

**Conclusion.** That the concept of the designating symbol and symbol manipulation does not emerge until the mid-fifties does not mean that the earlier steps were either inessential or less important. The total concept is the join of computability, physical realizability (and by multiple technologies), universality, the symbolic representation of processes (i.e. interpretability), and, finally, symbolic structure and designation. Each of the steps provided an essential part of the whole.

The first step in this chain, authored by Turing, is theoretically motivated, but the others all have deep empirical roots. We have been led by the evolution of the computer itself. The stored program principle arose out of the experience with Eniac. List processing arose out of the attempt to construct intelligent programs. It took its cue from the emergence of random access memories, which provided a clear physical realization of a designating symbol in the address. LISP arose out of the evolving experience with list processing.

## The Evidence

We come now to the evidence for the hypothesis that physical symbol systems are capable of intelligent action, and that general intelligent action calls for a physical symbol system. The hypothesis is an empirical generalization and not a theorem. We know of no way of demonstrating the connection between symbol systems and intelligence on purely logical grounds. Lacking such a demonstration, we must look at the facts. Our central aim, however, is not to review the evidence in detail, but to use the example before us to illustrate the proposition that computer science is a field of empirical inquiry. Hence, we will only indicate what kinds of evidence there is, and the general nature of the testing process.

The notion of physical symbol system had taken essentially its present form by the middle of the 1950's, and one can date from that time the growth of artificial intelligence as a coherent subfield of computer science. The twenty years of work since then has seen a continuous accumulation of empirical evidence of two main varieties. The first addresses itself to the *sufficiency* of physical symbol systems for producing intelligence, attempting to construct and test specific systems that have such a capability. The second kind of evidence addresses itself to the *necessity* of having a physical symbol system wherever intelligence is exhibited. It starts with Man, the intelligent system best known to us, and attempts to discover whether his cognitive activity can be explained as the working of a physical symbol system. There are other forms of evidence, which we will comment upon briefly later, but these two are the important ones. We will consider them in turn. The first is generally called artificial intelligence, the second, research in cognitive psychology.

**Constructing Intelligent Systems.** The basic paradigm for the initial testing of the germ theory of disease was: identify a disease; then look for the germ. An analogous paradigm has inspired much of the research in artificial intelligence: identify a task domain calling for intelligence; then construct a program for a digital computer

that can handle tasks in that domain. The easy and well-structured tasks were looked at first: puzzles and games, operations research problems of scheduling and allocating resources, simple induction tasks. Scores, if not hundreds, of programs of these kinds have by now been constructed, each capable of some measure of intelligent action in the appropriate domain.

Of course intelligence is not an all-or-none matter, and there has been steady progress toward higher levels of performance in specific domains, as well as toward widening the range of those domains. Early chess programs, for example, were deemed successful if they could play the game legally and with some indication of purpose; a little later, they reached the level of human beginners; within ten or fifteen years, they began to compete with serious amateurs. Progress has been slow (and the total programming effort invested small) but continuous, and the paradigm of construct-and-test proceeds in a regular cycle—the whole research activity mimicking at a macroscopic level the basic generate-and-test cycle of many of the AI programs.

There is a steadily widening area within which intelligent action is attainable. From the original tasks, research has extended to building systems that handle and understand natural language in a variety of ways, systems for interpreting visual scenes, systems for hand-eye coordination, systems that design, systems that write computer programs, systems for speech understanding—the list is, if not endless, at least very long. If there are limits beyond which the hypothesis will not carry us, they have not yet become apparent. Up to the present, the rate of progress has been governed mainly by the rather modest quantity of scientific resources that have been applied and the inevitable requirement of a substantial system-building effort for each new major undertaking.

Much more has been going on, of course, than simply a piling up of examples of intelligent systems adapted to specific task domains. It would be surprising and unappealing if it turned out that the AI programs performing these diverse tasks had nothing in common beyond their being instances of physical symbol systems. Hence, there has been great interest in searching for mechanisms possessed of generality, and for common components among programs performing a variety of tasks. This search carries the theory beyond the initial symbol system hypothesis to a more complete characterization of the particular kinds of symbol systems that are effective in artificial intelligence. In the second section of this paper, we will discuss one example of a hypothesis at this second level of specificity: the heuristic search hypothesis.

The search for generality spawned a series of programs designed to separate out general problem-solving mechanisms from the requirements of particular task domains. The General Problem Solver (GPS) was perhaps the first of these; while among its descendants are such contemporary systems as PLANNER and CONNIVER. The search for common components has led to generalized schemes of representation for goals and plans, methods for constructing discrimination nets, procedures for the control of tree search, pattern-matching mechanisms, and language-parsing systems. Experiments are at present under way to find convenient devices for representing sequences of time and tense, movement, causality and the like. More and more, it becomes possible to assemble large intelligent systems in a modular way from such basic components.

We can gain some perspective on what is going on by turning, again, to the analogy of the germ theory. If the first burst of research stimulated by that theory consisted largely in finding the germ to go with each disease, subsequent effort turned to learning what a germ was—to building on the basic qualitative law a new level of structure. In artificial intelligence, an initial burst of activity aimed at building intelligent programs for a wide variey of almost randomly selected tasks is giving way to more sharply targeted research aimed at understanding the common mechanisms of such systems.

**The Modeling of Human Symbolic Behavior.** The symbol system hypothesis implies that the symbolic behavior of man arises because he has the characteristics of a physical symbol system. Hence, the results of efforts to model human behavior with symbol systems become an important part of the evidence for the hypothesis, and research in artificial intelligence goes on in close collaboration with research in information processing psychology, as it is usually called.

The search for explanations of man's intelligent behavior in terms of symbol systems has had a large measure of success over the past twenty years; to the point where information processing theory is the leading contemporary point of view in cognitive psychology. Especially in the areas of problem solving, concept attainment, and long-term memory, symbol manipulation models now dominate the scene.

Research in information processing psychology involves two main kinds of empirical activity. The first is the conduct of observations and experiments on human behavior in tasks requiring intelligence. The second, very similar to the parallel activity in artificial intelligence, is the programming of symbol systems to model the observed human behavior. The psychological observations and experiments lead to the formulation of hypotheses about the symbolic processes the subjects are using, and these are an important source of the ideas that go into the construction of the programs. Thus, many of the ideas for the basic mechanisms of GPS were derived from careful analysis of the protocols that human subjects produced while thinking aloud during the performance of a problem-solving task.

The empirical character of computer science is nowhere more evident than in this alliance with psy-

chology. Not only are psychological experiments required to test the veridicality of the simulation models as explanations of the human behavior, but out of the experiments come new ideas for the design and construction of physical symbol systems.

**Other Evidence.** The principal body of evidence for the symbol system hypothesis that we have not considered is negative evidence: the absence of specific competing hypotheses as to how intelligent activity might be accomplished—whether by man or machine. Most attempts to build such hypotheses have taken place within the field of psychology. Here we have had a continuum of theories from the points of view usually labeled "behaviorism" to those usually labeled "Gestalt theory." Neither of these points of view stands as a real competitor to the symbol system hypothesis, and this for two reasons. First, neither behaviorism nor Gestalt theory has demonstrated, or even shown how to demonstrate, that the explanatory mechanisms it postulates are sufficient to account for intelligent behavior in complex tasks. Second, neither theory has been formulated with anything like the specificity of artificial programs. As a matter of fact, the alternative theories are sufficiently vague so that it is not terribly difficult to give them information processing interpretations, and thereby assimilate them to the symbol system hypothesis.

### Conclusion

We have tried to use the example of the Physical Symbol System Hypothesis to illustrate concretely that computer science is a scientific enterprise in the usual meaning of that term: that it develops scientific hypotheses which it then seeks to verify by empirical inquiry. We had a second reason, however, for choosing this particular example to illustrate our point. The Physical Symbol System Hypothesis is itself a substantial scientific hypothesis of the kind that we earlier dubbed "laws of qualitative structure." It represents an important discovery of computer science, which if borne out by the empirical evidence, as in fact appears to be occurring, will have major continuing impact on the field.

We turn now to a second example, the role of search in intelligence. This topic, and the particular hypothesis about it that we shall examine, have also played a central role in computer science, in general, and artificial intelligence, in particular.

## II. Heuristic Search

Knowing that physical symbol systems provide the matrix for intelligent action does not tell us how they accomplish this. Our second example of a law of qualitative structure in computer science addresses this latter question, asserting that symbol systems solve problems by using the processes of heuristic search. This generalization, like the previous one, rests on empirical evidence, and has not been derived formally from other premises. However, we shall see in a moment that it does have some logical connection with the symbol system hypothesis, and perhaps we can look forward to formalization of the connection at some time in the future. Until that time arrives, our story must again be one of empirical inquiry. We will describe what is known about heuristic search and review the empirical findings that show how it enables action to be intelligent. We begin by stating this law of qualitative structure, the Heuristic Search Hypothesis.

> *Heuristic Search Hypothesis.* The solutions to problems are represented as symbol structures. A physical symbol system exercises its intelligence in problem solving by search—that is, by generating and progressively modifying symbol structures until it produces a solution structure.

Physical symbol systems must use heuristic search to solve problems because such systems have limited processing resources; in a finite number of steps, and over a finite interval of time, they can execute only a finite number of processes. Of course that is not a very strong limitation, for all universal Turing machines suffer from it. We intend the limitation, however, in a stronger sense: we mean *practically* limited. We can conceive of systems that are not limited in a practical way, but are capable, for example, of searching in parallel the nodes of an exponentially expanding tree at a constant rate for each unit advance in depth. We will not be concerned here with such systems, but with systems whose computing resources are scarce relative to the complexity of the situations with which they are confronted. The restriction will not exclude any real symbol systems, in computer or man, in the context of real tasks. The fact of limited resources allows us, for most purposes, to view a symbol system as though it were a serial, one-process-at-a-time device. If it can accomplish only a small amount of processing in any short time interval, then we might as well regard it as doing things one at a time. Thus "limited resource symbol system" and "serial symbol system" are practically synonymous. The problem of allocating a scarce resource from moment to moment can usually be treated, if the moment is short enough, as a problem of scheduling a serial machine.

### Problem Solving

Since ability to solve problems is generally taken as a prime indicator that a system has intelligence, it is natural that much of the history of artificial intelligence is taken up with attempts to build and understand problem-solving systems. Problem solving has been discussed by philosophers and psychologists for two millenia, in discourses dense with the sense of mystery. If you think there is nothing problematic or mysterious about a symbol system solving problems, then you are

a child of today, whose views have been formed since mid-century. Plato (and, by his account, Socrates) found difficulty understanding even how problems could be *entertained*, much less how they could be solved. Let me remind you of how he posed the conundrum in the *Meno:*

> Meno: And how will you inquire, Socrates, into that which you know not? What will you put forth as the subject of inquiry? And if you find what you want, how will you ever know that this is what you did not know?

To deal with this puzzle, Plato invented his famous theory of recollection: when you think you are discovering or learning something, you are really just recalling what you already knew in a previous existence. If you find this explanation preposterous, there is a much simpler one available today, based upon our understanding of symbol systems. An approximate statement of it is:

> To state a problem is to designate (1) a *test* for a class of symbol structures (solutions of the problem), and (2) a *generator* of symbol structures (potential solutions). To solve a problem is to generate a structure, using (2), that satisfies the test of (1).

We have a problem if we know what we want to do (the test), and if we don't know immediately how to do it (our generator does not immediately produce a symbol structure satisfying the test). A symbol system can state and solve problems (sometimes) because it can generate and test.

If that is all there is to problem solving, why not simply generate at once an expression that satisfies the test? This is, in fact, what we do when we wish and dream. "If wishes were horses, beggars might ride." But outside the world of dreams, it isn't possible. To know how we would test something, once constructed, does not mean that we know how to construct it—that we have any generator for doing so.

For example, it is well known what it means to "solve" the problem of playing winning chess. A simple test exists for noticing winning positions, the test for checkmate of the enemy King. In the world of dreams one simply generates a strategy that leads to checkmate for all counter strategies of the opponent. Alas, no generator that will do this is known to existing symbol systems (man or machine). Instead, good moves in chess are sought by generating various alternatives, and painstakingly evaluating them with the use of approximate, and often erroneous, measures that are supposed to indicate the likelihood that a particular line of play is on the route to a winning position. Move generators there are; winning move generators there are not.

Before there can be a move generator for a problem, there must be a problem space: a space of symbol structures in which problem situations, including the initial and goal situations, can be represented. Move generators are processes for modifying one situation in the problem space into another. The basic characteristics of physical symbol systems guarantee that they can represent problem spaces and that they possess move generators. How, in any concrete situation they synthesize a problem space and move generators appropriate to that situation is a question that is still very much on the frontier of artificial intelligence research.

The task that a symbol system is faced with, then, when it is presented with a problem and a problem space, is to use its limited processing resources to generate possible solutions, one after another, until it finds one that satisfies the problem-defining test. If the system had some control over the order in which potential solutions were generated, then it would be desirable to arrange this order of generation so that actual solutions would have a high likelihood of appearing early. A symbol system would exhibit intelligence to the extent that it succeeded in doing this. Intelligence for a system with limited processing resources consists in making wise choices of what to do next.

### Search in Problem Solving

During the first decade or so of artificial intelligence research, the study of problem solving was almost synonymous with the study of search processes. From our characterization of problems and problem solving, it is easy to see why this was so. In fact, it might be asked whether it could be otherwise. But before we try to answer that question, we must explore further the nature of search processes as it revealed itself during that decade of activity.

**Extracting Information from the Problem Space.** Consider a set of symbol structures, some small subset of which are solutions to a given problem. Suppose, further, that the solutions are distributed randomly through the entire set. By this we mean that no information exists that would enable any search generator to perform better than a random search. Then no symbol system could exhibit more intelligence (or less intelligence) than any other in solving the problem, although one might experience better luck than another.

A condition, then, for the appearance of intelligence is that the distribution of solutions be not entirely random, that the space of symbol structures exhibit at least some degree of order and pattern. A second condition is that pattern in the space of symbol structures be more or less detectible. A third condition is that the generator of potential solutions be able to behave differentially, depending on what pattern it detected. There must be information in the problem space, and the symbol system must be capable of extracting and using it. Let us look first at a very simple example, where the intelligence is easy to come by.

Consider the problem of solving a simple algebraic equation:

$$AX + B = CX + D$$

The test defines a solution as any expression of the form, $X = E$, such that $AE + B = CE + D$. Now one could use as generator any process that would produce numbers which could then be tested by substituting in the latter equation. We would not call this an intelligent generator.

Alternatively, one could use generators that would make use of the fact that the original equation can be modified—by adding or subtracting equal quantities from both sides, or multiplying or dividing both sides by the same quantity—without changing its solutions. But, of course, we can obtain even more information to guide the generator by comparing the original expression with the form of the solution, and making precisely those changes in the equation that leave its solution unchanged, while at the same time, bringing it into the desired form. Such a generator could notice that there was an unwanted $CX$ on the right-hand side of the original equation, subtract it from both sides and collect terms again. It could then notice that there was an unwanted $B$ on the left-hand side and subtract that. Finally, it could get rid of the unwanted coefficient $(A - C)$ on the left-hand side by dividing.

Thus by this procedure, which now exhibits considerable intelligence, the generator produces successive symbol structures, each obtained by modifying the previous one; and the modifications are aimed at reducing the differences between the form of the input structure and the form of the test expression, while maintaining the other conditions for a solution.

This simple example already illustrates many of the main mechanisms that are used by symbol systems for intelligent problem solving. First, each successive expression is not generated independently, but is produced by modifying one produced previously. Second, the modifications are not haphazard, but depend upon two kinds of information. They depend on information that is constant over this whole class of algebra problems, and that is built into the structure of the generator itself: all modifications of expressions must leave the equation's solution unchanged. They also depend on information that changes at each step: detection of the differences in form that remain between the current expression and the desired expression. In effect, the generator incorporates some of the tests the solution must satisfy, so that expressions that don't meet these tests will never be generated. Using the first kind of information guarantees that only a tiny subset of all possible expressions is actually generated, but without losing the solution expression from this subset. Using the second kind of information arrives at the desired solution by a succession of approximations, employing a simple form of means-ends analysis to give direction to the search.

There is no mystery where the information that guided the search came from. We need not follow Plato in endowing the symbol system with a previous existence in which it already knew the solution. A moderately sophisticated generator-test system did the trick without invoking reincarnation.

**Search Trees.** The simple algebra problem may seem an unusual, even pathological, example of search. It is certainly not trial-and-error search, for though there were a few trials, there was no error. We are more accustomed to thinking of problem-solving search as generating lushly branching trees of partial solution possibilities which may grow to thousands, or even millions, of branches, before they yield a solution. Thus, if from each expression it produces, the generator creates $B$ new branches, then the tree will grow as $B^D$, where $D$ is its depth. The tree grown for the algebra problem had the peculiarity that its branchiness, $B$, equaled unity.

Programs that play chess typically grow broad search trees, amounting in some cases to a million branches or more. (Although this example will serve to illustrate our points about tree search, we should note that the purpose of search in chess is not to generate proposed solutions, but to evaluate (test) them.) One line of research into game-playing programs has been centrally concerned with improving the representation of the chess board, and the processes for making moves on it, so as to speed up search and make it possible to search larger trees. The rationale for this direction, of course, is that the deeper the dynamic search, the more accurate should be the evaluations at the end of it. On the other hand, there is good empirical evidence that the strongest human players, grandmasters, seldom explore trees of more than one hundred branches. This economy is achieved not so much by searching less deeply than do chess-playing programs, but by branching very sparsely and selectively at each node. This is only possible, without causing a deterioration of the evaluations, by having more of the selectivity built into the generator itself, so that it is able to select for generation just those branches that are very likely to yield important relevant information about the position.

The somewhat paradoxical-sounding conclusion to which this discussion leads is that search—successive generation of potentional solution structures—is a fundamental aspect of a symbol system's exercise of intelligence in problem solving but that amount of search is not a measure of the amount of intelligence being exhibited. What makes a problem a problem is not that a large amount of search is required for its solution, but that a large amount *would* be required if a requisite level of intelligence were not applied. When the symbolic system that is endeavoring to solve a problem knows enough about what to do, it simply proceeds directly towards its goal; but whenever its knowledge becomes inadequate, when it enters terra incognita, it

is faced with the threat of going through large amounts of search before it finds its way again.

The potential for the exponential explosion of the search tree that is present in every scheme for generating problem solutions warns us against depending on the brute force of computers—even the biggest and fastest computers—as a compensation for the ignorance and unselectivity of their generators. The hope is still periodically ignited in some human breasts that a computer can be found that is fast enough, and that can be programmed cleverly enough, to play good chess by brute-force search. There is nothing known in theory about the game of chess that rules out this possibility. Empirical studies on the management of search in sizable trees with only modest results make this a much less promising direction than it was when chess was first chosen as an appropriate task for artificial intelligence. We must regard this as one of the important empirical findings of research with chess programs.

**The Forms of Intelligence.** The task of intelligence, then, is to avert the ever-present threat of the exponential explosion of search. How can this be accomplished? The first route, already illustrated by the algebra example, and by chess programs that only generate "plausible" moves for further analysis, is to build selectivity into the generator: to generate only structures that show promise of being solutions or of being along the path toward solutions. The usual consequence of doing this is to decrease the rate of branching, not to prevent it entirely. Ultimate exponential explosion is not avoided—save in exceptionally highly structured situations like the algebra example—but only postponed. Hence, an intelligent system generally needs to supplement the selectivity of its solution generator with other information-using techniques to guide search.

Twenty years of experience with managing tree search in a variety of task environments has produced a small kit of general techniques which is part of the equipment of every researcher in artificial intelligence today. Since these techniques have been described in general works like that of Nilsson [1971], they can be summarized very briefly here.

In serial heuristic search, the basic question always is: what shall be done next? In tree search, that question, in turn, has two components: (1) from what node in the tree shall we search next, and (2) what direction shall we take from that node? Information helpful in answering the first question may be interpreted as measuring the relative distance of different nodes from the goal. Best-first search calls for searching next from the node that appears closest to the goal. Information helpful in answering the second question—in what direction to search—is often obtained, as in the algebra example, by detecting specific differences between the current nodal structure and the goal structure described by the test of a solution, and selecting actions that are relevant to reducing these particular kinds of differences. This is the technique known as means-ends analysis, which plays a central role in the structure of the General Problem Solver.

The importance of empirical studies as a source of general ideas in AI research can be demonstrated clearly by tracing the history, through large numbers of problem solving programs, of these two central ideas: best-first search and means-ends analysis. Rudiments of best-first search were already present, though unnamed, in the Logic Theorist in 1955. The General Problem Solver, embodying means-ends analysis, appeared about 1957—but combined it with modified depth-first search rather than best-first search. Chess programs were generally wedded, for reasons of economy of memory, to depth-first search, supplemented after about 1958 by the powerful alpha beta pruning procedure. Each of these techniques appears to have been reinvented a number of times, and it is hard to find general, task-independent theoretical discussions of problem solving in terms of these concepts until the middle or late 1960's. The amount of formal buttressing they have received from mathematical theory is still miniscule: some theorems about the reduction in search that can be secured from using the alpha-beta heuristic, a couple of theorems (reviewed by Nilsson [1971]) about shortest-path search, and some very recent theorems on best-first search with a probabilistic evaluation function.

**"Weak" and "Strong" Methods.** The techniques we have been discussing are dedicated to the control of exponential expansion rather than its prevention. For this reason, they have been properly called "weak methods"—methods to be used when the symbol system's knowledge or the amount of structure actually contained in the problem space are inadequate to permit search to be avoided entirely. It is instructive to contrast a highly structured situation, which can be formulated, say, as a linear programming problem, with the less structured situations of combinatorial problems like the traveling salesman problem or scheduling problems. ("Less structured" here refers to the insufficiency or nonexistence of relevant theory about the structure of the problem space.)

In solving linear programming problems, a substantial amount of computation may be required, but the search does not branch. Every step is a step along the way to a solution. In solving combinatorial problems or in proving theorems, tree search can seldom be avoided, and success depends on heuristic search methods of the sort we have been describing.

Not all streams of AI problem-solving research have followed the path we have been outlining. An example of a somewhat different point is provided by the work on theorem-proving systems. Here, ideas imported from mathematics and logic have had a strong influence on the direction of inquiry. For example, the use of heuristics was resisted when properties of com-

pleteness could not be proved (a bit ironic, since most interesting mathematical systems are known to be undecidable). Since completeness can seldom be proved for best-first search heuristics, or for many kinds of selective generators, the effect of this requirement was rather inhibiting. When theorem-proving programs were continually incapacitated by the combinatorial explosion of their search trees, thought began to be given to selective heuristics, which in many cases proved to be analogues of heuristics used in general problem-solving programs. The set-of-support heuristic, for example, is a form of working backwards, adapted to the resolution theorem proving environment.

**A Summary of the Experience.** We have now described the workings of our second law of qualitative structure, which asserts that physical symbol systems solve problems by means of heuristic search. Beyond that, we have examined some subsidiary characteristics of heuristic search, in particular the threat that it always faces of exponential explosion of the search tree, and some of the means it uses to avert that threat. Opinions differ as to how effective heuristic search has been as a problem solving mechanism—the opinions depending on what task domains are considered and what criterion of adequacy is adopted. Success can be guaranteed by setting aspiration levels low—or failure by setting them high. The evidence might be summed up about as follows. Few programs are solving problems at "expert" professional levels. Samuel's checker program and Feigenbaum and Lederberg's DENDRAL are perhaps the best-known exceptions, but one could point also to a number of heuristic search programs for such operations research problem domains as scheduling and integer programming. In a number of domains, programs perform at the level of competent amateurs: chess, some theorem-proving domains, many kinds of games and puzzles. Human levels have not yet been nearly reached by programs that have a complex perceptual "front end": visual scene recognizers, speech understanders, robots that have to maneuver in real space and time. Nevertheless, impressive progress has been made, and a large body of experience assembled about these difficult tasks.

We do not have deep theoretical explanations for the particular pattern of performance that has emerged. On empirical grounds, however, we might draw two conclusions. First, from what has been learned about human expert performance in tasks like chess, it is likely that any system capable of matching that performance will have to have access, in its memories, to very large stores of semantic information. Second, some part of the human superiority in tasks with a large perceptual component can be attributed to the special-purpose built-in parallel processing structure of the human eye and ear.

In any case, the quality of performance must necessarily depend on the characteristics both of the problem domains and of the symbol systems used to tackle them. For most real-life domains in which we are interested, the domain structure has not proved sufficiently simple to yield (so far) theorems about complexity, or to tell us, other than empirically, how large real-world problems are in relation to the abilities of our symbol systems to solve them. That situation may change, but until it does, we must rely upon empirical explorations, using the best problem solvers we know how to build, as a principal source of knowledge about the magnitude and characteristics of problem difficulty. Even in highly structured areas like linear programming, theory has been much more useful in strengthening the heuristics that underlie the most powerful solution algorithms than in providing a deep analysis of complexity.

## Intelligence Without Much Search

Our analysis of intelligence equated it with ability to extract and use information about the structure of the problem space, so as to enable a problem solution to be generated as quickly and directly as possible. New directions for improving the problem-solving capabilities of symbol systems can be equated, then, with new ways of extracting and using information. At least three such ways can be identified.

**Nonlocal Use of Information.** First, it has been noted by several investigators that information gathered in the course of tree search is usually only used *locally*, to help make decisions at the specific node where the information was generated. Information about a chess position, obtained by dynamic analysis of a subtree of continuations, is usually used to evaluate just that position, not to evaluate other positions that may contain many of the same features. Hence, the same facts have to be rediscovered repeatedly at different nodes of the search tree. Simply to take the information out of the context in which it arose and use it generally does not solve the problem, for the information may be valid only in a limited range of contexts. In recent years, a few exploratory efforts have been made to transport information from its context of origin to other appropriate contexts. While it is still too early to evaluate the power of this idea, or even exactly how it is to be achieved, it shows considerable promise. An important line of investigation that Berliner [1975] has been pursuing is to use causal analysis to determine the range over which a particular piece of information is valid. Thus if a weakness in a chess position can be traced back to the move that made it, then the same weakness can be expected in other positions descendant from the same move.

The HEARSAY speech understanding system has taken another approach to making information globally available. That system seeks to recognize speech strings by pursuing a parallel search at a number of different

levels: phonemic, lexical, syntactic, and semantic. As each of these searches provides and evaluates hypotheses, it supplies the information it has gained to a common "blackboard" that can be read by all the sources. This shared information can be used, for example, to eliminate hypotheses, or even whole classes of hypotheses, that would otherwise have to be searched by one of the processes. Thus, increasing our ability to use tree-search information nonlocally offers promise for raising the intelligence of problem-solving systems.

**Semantic Recognition Systems.** A second active possibility for raising intelligence is to supply the symbol system with a rich body of semantic information about the task domain it is dealing with. For example, empirical research on the skill of chess masters shows that a major source of the master's skill is stored information that enables him to recognize a large number of specific features and patterns of features on a chess board, and information that uses this recognition to propose actions appropriate to the features recognized. This general idea has, of course, been incorporated in chess programs almost from the beginning. What is new is the realization of the number of such patterns and associated information that may have to be stored for master-level play: something of the order of 50,000.

The possibility of substituting recognition for search arises because a particular, and especially a rare, pattern can contain an enormous amount of information, provided that it is closely linked to the structure of the problem space. When that structure is "irregular," and not subject to simple mathematical description, then knowledge of a large number of relevant patterns may be the key to intelligent behavior. Whether this is so in any particular task domain is a question more easily settled by empirical investigation than by theory. Our experience with symbol systems richly endowed with semantic information and pattern-recognizing capabilities for accessing it is still extremely limited.

The discussion above refers specifically to semantic information associated with a recognition system. Of course, there is also a whole large area of AI research on semantic information processing and the organization of semantic memories that falls outside the scope of the topics we are discussing in this paper.

**Selecting Appropriate Representations.** A third line of inquiry is concerned with the possibility that search can be reduced or avoided by selecting an appropriate problem space. A standard example that illustrates this possibility dramatically is the mutilated checkerboard problem. A standard 64 square checkerboard can be covered exactly with 32 tiles, each a $1 \times 2$ rectangle covering exactly two squares. Suppose, now, that we cut off squares at two diagonally opposite corners of the checkerboard, leaving a total of 62 squares. Can this mutilated board be covered exactly with 31 tiles? With (literally) heavenly patience, the impossibility of achieving such a covering can be demonstrated by trying all possible arrangements. The alternative, for those with less patience, and more intelligence, is to observe that the two diagonally opposite corners of a checkerboard are of the same color. Hence, the mutilated checkerboard has two less squares of one color than of the other. But each tile covers one square of one color and one square of the other, and any set of tiles must cover the same number of squares of each color. Hence, there is no solution. How can a symbol system discover this simple inductive argument as an alternative to a hopeless attempt to solve the problem by search among all possible coverings? We would award a system that found the solution high marks for intelligence.

Perhaps, however, in posing this problem we are not escaping from search processes. We have simply displaced the search from a space of possible problem solutions to a space of possible representations. In any event, the whole process of moving from one representation to another, and of discovering and evaluating representations, is largely unexplored territory in the domain of problem-solving research. The laws of qualitative structure governing representations remain to be discovered. The search for them is almost sure to receive considerable attention in the coming decade.

## Conclusion

That is our account of symbol systems and intelligence. It has been a long road from Plato's *Meno* to the present, but it is perhaps encouraging that most of the progress along that road has been made since the turn of the twentieth century, and a large fraction of it since the midpoint of the century. Thought was still wholly intangible and ineffable until modern formal logic interpreted it as the manipulation of formal tokens. And it seemed still to inhabit mainly the heaven of Platonic ideals, or the equally obscure spaces of the human mind, until computers taught us how symbols could be processed by machines. A.M. Turing, whom we memorialize this morning, made his great contributions at the mid-century crossroads of these developments that led from modern logic to the computer.

**Physical Symbol Systems.** The study of logic and computers has revealed to us that intelligence resides in physical symbol systems. This is computer sciences's most basic law of qualitative structure.

Symbol systems are collections of patterns and processes, the latter being capable of producing, destroying and modifying the former. The most important properties of patterns is that they can designate objects, processes, or other patterns, and that, when they designate processes, they can be interpreted. Interpretation means carrying out the designated process. The two most significant classes of symbol systems with which we are acquainted are human beings and computers.

Our present understanding of symbol systems grew, as indicated earlier, through a sequence of stages. Formal logic familiarized us with symbols, treated syntactically, as the raw material of thought, and with the idea of manipulating them according to carefully defined formal processes. The Turing machine made the syntactic processing of symbols truly machine-like, and affirmed the potential universality of strictly defined symbol systems. The stored-program concept for computers reaffirmed the interpretability of symbols, already implicit in the Turing machine. List processing brought to the forefront the denotational capacities of symbols, and defined symbol processing in ways that allowed independence from the fixed structure of the underlying physical machine. By 1956 all of these concepts were available, together with hardware for implementing them. The study of the intelligence of symbol systems, the subject of artificial intelligence, could begin.

**Heuristic Search.** A second law of qualitative structure for AI is that symbol systems solve problems by generating potential solutions and testing them, that is, by searching. Solutions are usually sought by creating symbolic expressions and modifying them sequentially until they satisfy the conditions for a solution. Hence symbol systems solve problems by searching. Since they have finite resources, the search cannot be carried out all at once, but must be sequential. It leaves behind it either a single path from starting point to goal or, if correction and backup are necessary, a whole tree of such paths.

Symbol systems cannot appear intelligent when they are surrounded by pure chaos. They exercise intelligence by extracting information from a problem domain and using that information to guide their search, avoiding wrong turns and circuitous bypaths. The problem domain must contain information, that is, some degree of order and structure, for the method to work. The paradox of the *Meno* is solved by the observation that information may be remembered, but new information may also be extracted from the domain that the symbols designate. In both cases, the ultimate source of the information is the task domain.

**The Empirical Base.** Artificial intelligence research is concerned with how symbol systems must be organized in order to behave intelligently. Twenty years of work in the area has accumulated a considerable body of knowledge, enough to fill several books (it already has), and most of it in the form of rather concrete experience about the behavior of specific classes of symbol systems in specific task domains. Out of this experience, however, there have also emerged some generalizations, cutting across task domains and systems, about the general characteristics of intelligence and its methods of implementation.

We have tried to state some of these generalizations this morning. They are mostly qualitative rather than mathematical. They have more the flavor of geology or evolutionary biology than the flavor of theoretical physics. They are sufficiently strong to enable us today to design and build moderately intelligent systems for a considerable range of task domains, as well as to gain a rather deep understanding of how human intelligence works in many situations.

**What Next?** In our account today, we have mentioned open questions as well as settled ones; there are many of both. We see no abatement of the excitement of exploration that has surrounded this field over the past quarter century. Two resource limits will determine the rate of progress over the next such period. One is the amount of computing power that will be available. The second, and probably the more important, is the number of talented young computer scientists who will be attracted to this area of research as the most challenging they can tackle.

A.M. Turing concluded his famous paper on "Computing Machinery and Intelligence" with the words:

> "We can only see a short distance ahead, but we can see plenty there that needs to be done."

Many of the things Turing saw in 1950 that needed to be done have been done, but the agenda is as full as ever. Perhaps we read too much into his simple statement above, but we like to think that in it Turing recognized the fundamental truth that all computer scientists instinctively know. For all physical symbol systems, condemned as we are to serial search of the problem environment, the critical question is always: What to do next?

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# The Engineering Design Research Center of Carnegie Mellon University

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*Invited Paper*

*The Engineering Design Research Center (EDRC) promotes the establishment and dissemination of a scientific basis for design based on an interdisciplinary approach to research and education. The Center's vision is that a scientific framework for design can exploit rapid advances in computer and communications technologies to serve the competitive need for reduced product development cycles, improved quality and reliability, and lower cost. Basic notions of the product cycle underlie the Center's strategic plan, a framework of research thrusts leading from barriers in design science to goals and vision. As an NSF Engineering Research Center, EDRC conducts cross-educational and industrial programs in parallel with research. Three key features distinguish EDRC: broad cross-disciplinary fertilization; industrial partners who actively participate in research; and a broad and diverse educational program. This paper presents two case studies of interdisciplinary research approaches and further describes how industry has helped inspire novel opportunities to improve and calibrate research methodologies.*

## I. Introduction

Engineering design is the core of product and process development. The ability to design the highest quality products and processes in the shortest time is vital to U.S. industry. By the year 2000 a scientific basis of design will produce a collection of methodologies to help designers exploit advances in computers and communications more fully and perform better design as defined by improved product quality, reduced development cycles, and lower lifecycle costs. The Engineering Design Research Center focuses on the development of fundamentals of design science, methodologies for the creation of products and processes, and computational tools for improved design practice. These products of research, created in partnership with industry and government, will contribute to the establishment of a scientific basis for design practice.

Based largely on the transfer of concepts and methods across disciplines, design science will spawn a new generation of methodology-driven tools whose performance will accelerate and integrate the numerous phases of product development. Whereas today it is difficult for designers specializing in a single domain to access more than a handful of tools on a small network of machines, in 20 years teams of designers dispersed worldwide will work cooperatively across multiple domains, invoking a large number of computer programs, browsing voluminous internal and external information and data bases, and capturing and sharing design data in various forms.

The four principal goals of EDRC are:

1) To make a significant contribution to design science in the form of methodologies, computational tools, and environments for engineering design.
2) To educate a new generation of engineering design practitioners, educators, and researchers for industry and academia.
3) To infuse the engineering curriculum with engineering design textbooks and other course materials,

Manuscript received Nov. 7, 1991; revised Mar. 26, 1992.

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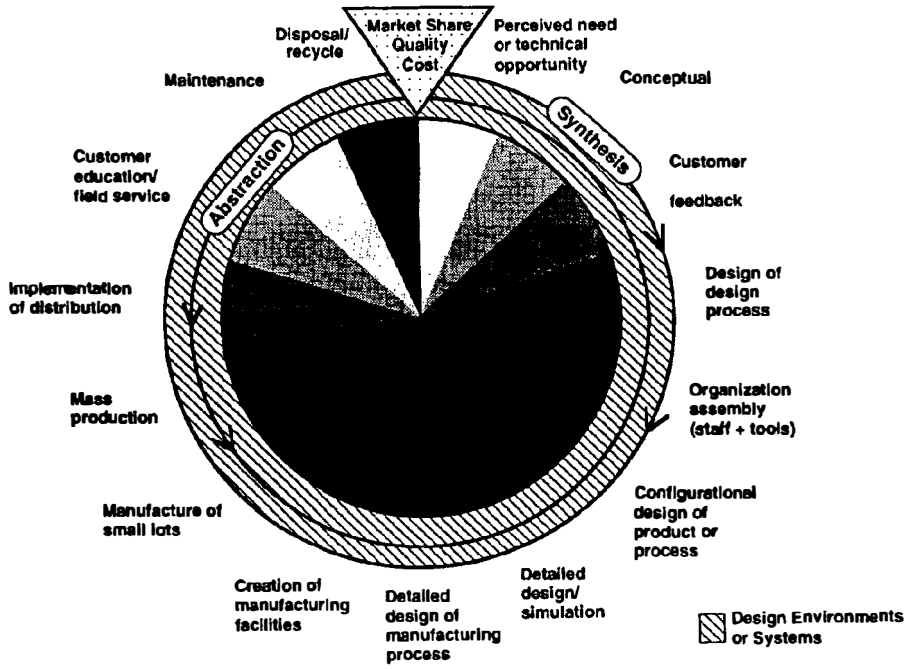



Fig. 1. The product cycle.

courses, and an optional undergraduate minor in engineering design.

4) To collaborate with industry to support improved design practice by exchanging knowledge, people, and software tools.

## II. Strategic Plan for EDRC Research

### A. Research Vision

The Engineering Design Research Center strives to lead in the development and integration of design methodologies that are grounded in a scientific framework and targeted at improving design practice in U.S. industry. The Center's research vision consists of three interrelated elements:

1) The enrichment of design science, that is, the development of a collection of design methodologies.
2) The embodiment of design methodologies in computer-based tools.
3) The development of an environment to support teams of dispersed designers working in diverse domains.

These three elements provide the essential link between design research and practice inherent in the Center's vision. Motivating the selection of strategic research issues to achieve this vision is the basic notion of the product cycle.

### B. The Product Cycle

Three information flows in the typical product cycle, as presented in Fig. 1, are the starting point for EDRC research. This cycle represents a recursive sequence of phases extending from perceived customer need or technical opportunity to disposal and recycling. Driving the creation of a product are the first two information flows: synthesis and abstraction. Synthesis focuses on the downward information flow in the product cycle in which alternatives are systematically created and selected. On the other hand, downstream concerns, such as performance and manufacturability, determine constraints on possible alternatives. These constraints need to be accessible at every stage of the product creation cycle where they may influence the synthesis process. This second information flow thus represents an abstraction process, since very detailed downstream information needs to be presented upstream in a compact and usable fashion. The third information flow provides environments that facilitate both synthesis and abstraction.

Traditional design tools and methods have focused on the detailed design phases located midway through the product cycle, as shown by the darkest phases in Fig. 1. EDRC's concepts, methods and tools seek to further encompass both earlier and later phases in the product cycle, which have heretofore lacked adequate support. This increased coverage is indicated by shading gradations in Fig. 1.

### C. Strategic Plan

EDRC operates under a strategic plan that guides research and also serves to evaluate progress. Deriving from a basic understanding of the product cycle, the plan progresses from perceived barriers in the development of science-based design to goals based on the vision, as shown in

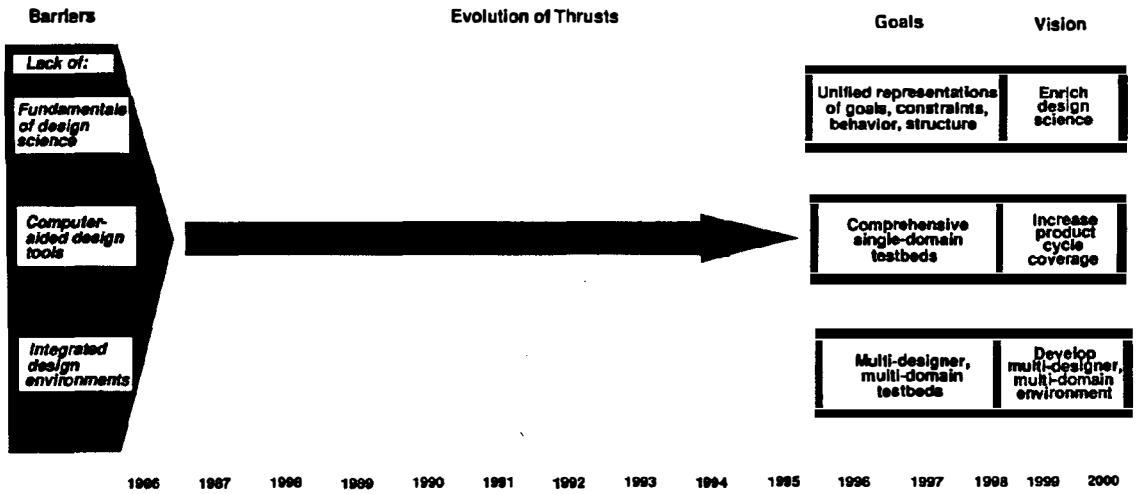



Fig. 2. Trajectory from barriers to EDRC goals and vision.

Fig. 2. The barriers refer to the missing ingredients of science-based design in the areas of fundamentals of design science, computer-aided design tools, and integrated design environments. EDRC research has based its selection of these barriers on the hypothesis that they will lead directly to *simultaneous* advances in design science and in practical science-based design tools.

The specific research goals of the strategic plan are:

1) **The development of unified representations of goals, constraints, behavior, and structure in various domains.** Design goals specify the criteria for measuring the quality of a candidate design (e.g., functionality, cost, reliability, manufacturability, etc.) Constraints limit the space of feasible designs by defining acceptable values for design parameters. As design goals are refined by constraints, a desired behavior emerges, which in turn produces a structure of the physical or abstract result. This research goal is EDRC's primary contribution to the emergence and enrichment of a new design science.
2) **The construction of comprehensive single-domain design testbeds.** The center draws on expertise in its four basic disciplines of chemical, civil, electrical, and mechanical engineering to construct cross-disciplinary methodologies for the design domains of buildings, computers, chemical processes, and automotive components. This research goal is aimed at increased coverage of the product cycle.
3) **The development of multidesigner multidomain testbeds.** EDRC efforts in coordinating and managing design organizations, projects, and information will yield domain-independent design environments to facilitate collaborative work by designers of diverse specialties in the creation of artifacts. This research goal serves the vision of an underlying design support environment.

Leading from barriers is a network of thrusts[2] evolving over time and integrating in a progression toward the three goals of the EDRC strategic plan.

## III. Organization and Thrusts

EDRC is organized into three laboratories—synthesis, design for manufacturing, and design systems—which emphasize the key information flows and aspects of integration previously identified. Synthesis addresses the downward information flow in the product cycle; design for manufacturing treats the upward information flow; and design systems focuses on the efficient support of all information flows.

### A. The Synthesis Laboratory

*1) Objectives:* The synthesis laboratory focuses on improving the integration of engineering systems at the preliminary stages of design using methodologies and computer tools for the generation and selection of alternatives. Emphasis is on the selection of the topology as well as the design parameters that define a given system (e.g., the structure of a building, a process flowsheet, a VLSI circuit, or an automotive component).

Decisions made at the preliminary stages of a design usually produce the greatest impact in terms of the cost, quality and manufacturability of a product or process. Yet the synthesis of engineering systems is still an area that is not well developed or understood. Among the major questions and challenges are:

1) Given the usually very large number of alternatives for synthesizing a design, how can representations of design spaces and search algorithms be used to effectively examine many design alternatives?

[2] The names of thrusts that appear in this document are shown in italics.

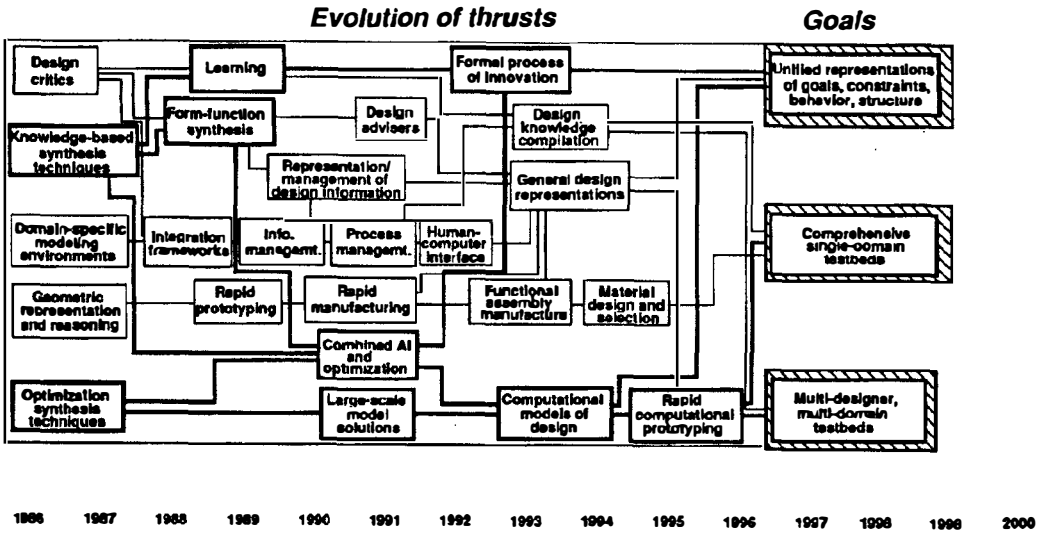



Fig. 3. Research path of synthesis laboratory.

2) How do we process qualitative design knowledge that is often diverse, incomplete, and often uncertain in nature?
3) Since the design of engineering systems requires both qualitative and quantitative evaluations, how do we combine paradigms for qualitative reasoning with quantitative analysis and optimization?
4) How can we account for the coupling of decisions and complex analysis models that usually prevents straightforward decompositions of synthesis problems?
5) How can learning by human beings and by computer tools be performed to improve the design process?

*2) Evolution of Thrusts:* The Synthesis Lab is concerned with the development of design methodologies that are based on a broad spectrum of symbolic, enumerative, and numerical techniques. It has targeted a wide variety of applications and involves researchers in chemical, civil, mechanical, and electrical engineering; architecture; computer science; and operations research. Our ultimate aim is to identify and generalize different classes of design problems across different domains, and to establish a roadmap for the mapping of solution techniques with design problems.

In the first three years, most of the projects in the Synthesis Laboratory addressed domain-specific applications in which two major design paradigms were explored: *knowledge-based synthesis techniques* and *optimization synthesis techniques* (see blocks in Fig. 3). In the former, qualitative knowledge of design problems was represented and processed through symbolic reasoning systems [1]. As for optimization techniques, both nonlinear (NLP) [2] and mixed-integer nonlinear programming (MINLP) techniques [3]–[5] were developed. From initial experience in these projects four new thrusts emerged: *form-function synthesis, learning, combined AI and optimization*, and *large-scale model solution* (see blocks in Fig. 3).

In *form-function synthesis*, the objective is to develop synthesis methodologies that can accurately account for interactions between the form of a designed artifact and its function or behavior. Early work investigated methods for abstracting form-function relations in electromechanical designs using parametric nonlinear programming [6]. Other research explored the systematic generation of alternative design topologies for two-dimensional layouts.[3] A project on VLSI synthesis developed SAW (System Architect's Workbench), a method for generating a design at the logic and register-transfer level from a behavioral or program-like description of a system [7]. A collaboration is tying the behavioral synthesis capabilities of SAW with the specification synthesis capabilities of MICON for handling off-the-shelf standard components [8]. Work is also underway on incorporating considerations of function in shape and solids grammars which have concentrated on aspects of form [9]. The objective is to develop an attribute algebra to complement the object algebra for simultaneous form-function synthesis.

The goal of *learning* is to assist in the acquisition, use and transfer of knowledge in realistic design contexts. Initial work explored the potential of Soar, a system which combines a rich set of general or "weak" problem-solving methods and the ability to "learn" by generating new chunks of knowledge from successful solutions of subproblems [10]. Cross-disciplinary work with civil engineering led to the development of a new approach for knowledge acquisition for learning that was applied to the design of bridges [11]. Collaboration with chemical engineering led to CPD-Soar, a prototype for synthesizing distillation sequences [12].

*Combined AI and optimization* is developing computational and conceptual frameworks for integrating qualitative

[3] For a more detailed description of layout, see case study 2 herein.

reasoning with quantitative analysis and optimization. A project in mixed integer nonlinear programming (MINLP) is developing computational schemes in which qualitative and quantitative aspects in terms of logic and heuristics are integrated within optimization techniques so as to expedite the search without compromising the optimality of the solutions whenever possible [13]. Other work is applying logical methods and mathematical programming theory to the identification of logical constraints that can limit the search in large combinatorial design problems [14]. The thrust has also been working on the conceptual design of mechanical systems and focuses on the generation of structural topologies to produce design innovations [15].

*Large-scale model solution* was motivated by exposure to industrial case studies which indicated that real problems were often one to several orders of magnitude larger than the academic examples used to illustrate methodologies. The specific objective of this thrust is to develop large-scale methodologies for design-oriented optimization models. One key accomplishment has been the development of a parallel branch and bound technique for solving the asymmetric traveling salesman problem [16]. Problems with up to 7 000 cities were solved to optimality in less than 20 minutes on a BBN Butterfly computer. These are among the largest problems that have been reported in the literature.

### *B. The Design for Manufacturing Laboratory*

*1) Objectives:* Early design decisions frequently restrict the design space to solutions that may be suboptimal regarding product manufacture. In many instances, designers do not sufficiently consider or evaluate appropriate design alternatives, nor are they aware that certain decisions may pose downstream problems. This inevitably leads to iterations, delays, and cost overruns. Product designers need to consider numerous candidate manufacturing processes simultaneously. They must also consider quality, cost, lead time, availability of subcomponents, and much more. They must examine a product from a number of diverse perspectives. Most likely, designers make many decisions based on intuition because of time constraints or the unavailability of people who might have the necessary information.

The objective of the Design for Manufacturing Laboratory is to bring downstream concerns, such as manufacturability, assemblability, and repairability, into the earlier phases of the design process. Achieving this objective requires two forms of abstraction. The first abstracts information about the design that is pertinent to the manufacturing process, such as geometry and properties of the manufacturing medium. The second abstracts information about the manufacturing process that would constrain the possible design alternatives. These constraints would guide the design process into generating alternatives that could be effectively manufactured using the given facilities. By moving downstream concerns up into the design process we should be able to produce higher quality artifacts at lower cost and in less time. The costly experimental "design-prototype-evaluate" cycle would be replaced by a process which produced a product that was "correct the first time." Achieving this objective presents several key issues:

1) For each individual manufacturing process, how can a theory be developed that abstracts the essential features of the process relevant to design? How can a methodology be developed that uses these abstractions to synthesize design alternatives?
2) Most contemporary artifacts are produced by several different manufacturing processes. Can we develop a system capable of reasoning across a range of manufacturing processes and resolving conflicts among constraints posed by individual manufacturing processes?
3) The effectiveness of an integrated design/manufacturing environment must be demonstrated through the actual construction of artifacts in a timely manner. How do we develop rapid prototyping facilities that embrace a multitude of manufacturing processes?

*2) Evolution of Thrusts:* Two major research paths in the Design for Manufacturing Laboratory are illustrated in Fig. 4: theory and experimentation. The theoretical path provides the basis for abstraction and reasoning about the manufacturing processes; the experimental path provides the rapid prototyping capability for validating theoretical results.

Historically, a concern with geometry has dominated manufacturing. Thus, initial research focused on the representation and analysis of geometry as applied to manufacturing. Research in *geometric representation and reasoning* produced the nonmanifold representation that formed the basis of the Noodles system [17]. Operators added to the system facilitate extraction of shape features from the geometric models [18]. These operators provided the basis by which *design critics* could analyze the geometry with respect to individual manufacturing processes.

The next logical step in the evolution of the theoretical path was to expand from analysis to synthesis in *form-function synthesis*, which is shared with the Synthesis Laboratory. Experience in that thrust indicated that the coupling between information about form and information about function was very loose and contained in multiple databases separated by several software tools. In *representation and management of design information*, we begin to experiment with ways to utilize form and function information simultaneously during the design process. We feel we have come close to making geometry just another attribute of a system, as opposed to an overwhelming attribute from which all other attributes flow. *Design advisers* builds on the above work by endowing the initially passive critics with active advisory capabilities in the design process.

In the future, we will attempt to generalize techniques of representation, analysis, abstraction, and modularity. In particular, we will start with *general design representations*. As we expand the representational work we will move into *functional assembly manufacture* thrust. This work is based upon *learning* research in the Synthesis Laboratory. We also foresee the need to initiate research in *material design and*

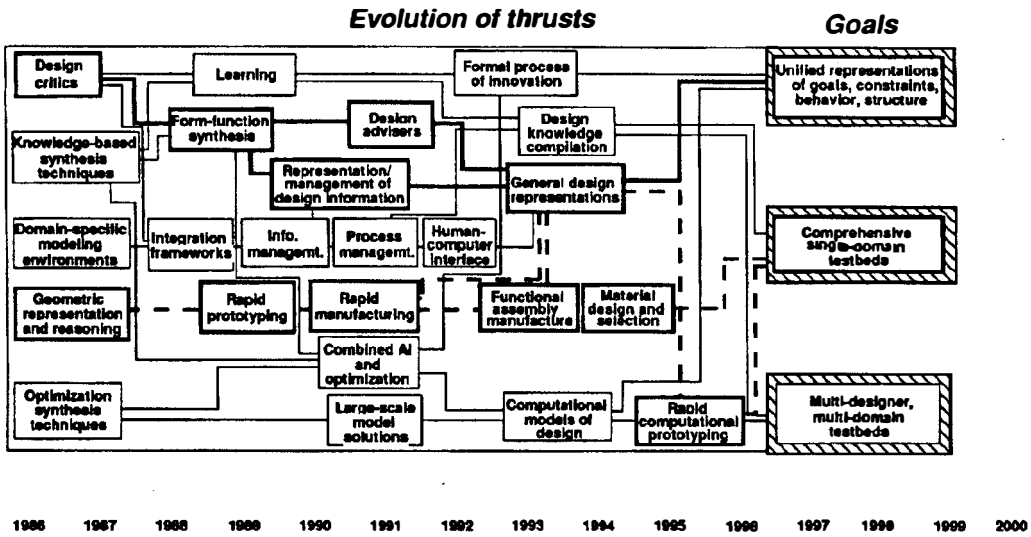



Fig. 4. Research path of design-for-manufacturing laboratory.

*selection.* The property of materials is an important aspect in the final form and function of an artifact.

The second major research thrust path of the laboratory is the physical production of prototypes. Coupling directly to a manufacturing process raises several issues which might otherwise be overlooked. *Rapid physical prototyping* started by coupling the Noodles representation with the stereolithography apparatus (SLA) (a commercial process for building plastic prototype models directly from liquid photopolymers by laser scanning).[4] The next step will be to incorporate multiple manufacturing processes in *functional assembly manufacture. General design representations* will provide a firm basis for *functional assembly manufacture*, in much the same way that Noodles became the underlying framework for linking stereolithography and thermal spraying.

As we look to the future we can envision a time when there will be no need for a physical prototype. *Rapid computational prototyping* will provide a virtual reality in which a designer can interact with an apparent three-dimensional version of the completed artifact.

### C. The Design Systems Laboratory

*1) Objectives:* We expect future computer design environments to provide a collection of intelligent design tools and databases running on heterogeneous computer networks, assisting teams of designers in coordinating activities, automating parts of the design process, and capturing and reusing information gleaned from previous designs. The objective of the Design Systems Laboratory is to develop the conceptual and methodological foundations of such tightly coupled multiuser multidomain design environments.

[4]For a more detailed description of the rapid prototyping process, see case study 1 herein.

Our research thus seeks to develop a design environment that integrates synthesis and analysis tools developed within both the Synthesis and the Design for Manufacturing Laboratories, and to support the information flows through various phases of the product cycle. As such, research focuses on system-level issues of integrating collections of specific tools and repositories of information. This work seeks to answer questions such as:

1) How can design information be effectively captured, represented, organized, and reused? How can the designer's goals be captured and represented?
2) What kinds of support can the design environment provide for managing the overall design process?
3) What types of human-computer interaction can most effectively support the design process (e.g., interfaces, information displays)?
4) Given that the design environment is a large, evolving software system, what methods can be used to ease the task of maintaining and reconfiguring the design environment as new design tools, databases, and domains are added?

Our research strategy includes both individual explorations of alternative approaches in a variety of task domains and a new integrated effort to develop a working design environment for a specific multidisciplinary task: the engineering design of a new product idea, a wearable computer.[5]

*2) Evolution of Thrusts:* The evolution of research thrusts within the Design Systems Laboratory is highlighted in Fig. 5. In its initial years, the Design Systems Laboratory focused on *Domain-specific modeling environments, design critics*, and *integration frameworks*. This research led to the development of specific design systems in domains such as building design (IBDE) [19] and equational modeling

[5]Discussion of the wearable computer can be found herein.

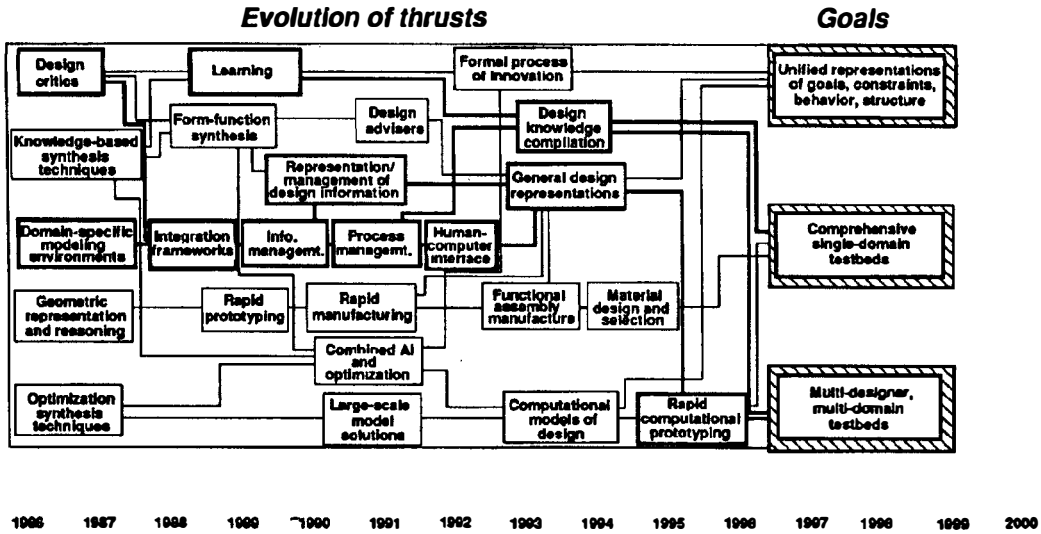



Fig. 5. Research path of design systems laboratory.

(ASCEND) [20], which provided valuable initial experience in understanding such issues as how to integrate collections of tools into a complete design system, how to interface to users, and how to represent design information in a useful form.

Current work in *representation and management of design information* explores the representation, capture, organization, and reuse of design information across a range of design domains, from preconceptual design through final fabrication.

A second active research thrust concerns *design process management*: the issue of how to coordinate a variety of design tools or processes to achieve overall design goals. This research has produced new methods for knowledge-based planning of design tasks [21] and for automated exploration of design spaces by collections of asynchronous processes [22].

A third active research thrust, *human-computer interface*, is concerned with how best to configure the interaction between design system and designers. At present our research in this area concentrates on interfaces for directly manipulating and evaluating virtual designs; conceptual modeling of users to guide interface design; and *in situ* evaluation of design systems and interfaces.

The fourth current research thrust, *learning*, is looking at how computer design aids can improve through experience. Current work centers on how to capture, represent, and index information about past designs so that it can be easily accessed and reused in subsequent design efforts.

## IV. The Unique Character of EDRC

Three key dynamics characterize the unique environment of EDRC. First is fertilization across thrusts, laboratories, and disciplines. The *form-function synthesis* thrust, for example, spans both the Synthesis and the Design for Manufacturing Laboratories. It combines the former's development of methods for synthesizing systems or components, in which form or geometry is key, with the latter's emphasis on introducing downstream functional considerations in the early design stages.

The cross-fertilization of research laboratories and thrusts is complemented by an atypical cross-disciplinary research environment. For example, work on ASCEND, a system for the rapid mathematical modeling of complex processes, blends expertise in chemical engineering, operations research, graphic design and rhetoric because the research team considers the interaction between the human user and the computer program as important a research focus as the program itself.

A second key dynamic of EDRC is industrial collaboration. Many of the 40 industrial members, who range from the automotive and electronics to the chemical and petroleum industries, derive benefits in cost and time savings from the center. Some industrial memberships are themselves cross-disciplinary collaborations. A three-way partnership of companies as diverse as Cray Research, a manufacturerer of supercomputers; Air Products, a manufacturer of gas processing and chemicals; and Aspen Technologies, a vendor of process simulation software, jointly sponsors EDRC research to incorporate mixed-integer nonlinear programming techniques into commercial process simulators.

The third key dynamic of EDRC is its educational mission. The Center imparts to students at the graduate and undergraduate levels a fundamental understanding of design issues and methodologies that address them. Graduate courses serve the dual function of presenting generic cross-disciplinary design methodologies and applying them to design problems within the students' domains of study. An engineering minor option in design, an engineering

design textbook series, and the incorporation of design methodologies into new freshman engineering courses are examples of the Center's activities at the undergraduate level.

The synergism between strategically targeted cross-disciplinary research, industrial bonding, and education makes EDRC a unique place for design research and education. The Center involves faculty and students from six of seven schools of the university: engineering (six departments), computer science, fine arts, industrial administration, urban and public affairs, and the humanities. Cross-disciplinary collaborative efforts also extend to other universities and design centers in the United States and abroad.

## V. Two EDRC Case Studies

Two types of cross-disciplinary research may be traced in EDRC research: simultaneous cross-disciplinarity and sequential cross-disciplinarity. In the former, research is cross-disciplinary from the outset because the emphasis is on vertically integrated systems which span the entire life-cycle in one artifact domain. Other EDRC research thrusts pursue a sequential three-step cross-disciplinary approach. The first step is the development of a methodology that addresses a particular design concern in one discipline and reflects the researcher's in-depth domain knowledge. The second step is experimentation with that methodology across disciplines, which often entails expansion to "industrial grade" problems. In the third step, the resulting generic methodology is reapplied to the originating discipline, which usually leads to vastly expanded generality and scope. Although the first step could be performed in a single-investigator research environment, subsequent steps are possible only in an interdisciplinary research environment that is coupled with industry. The following two case studies illustrate the simultaneous and sequential cross-disciplinary approaches, respectively.

### *A. Case Study #1: Rapid Tool Manufacturing*

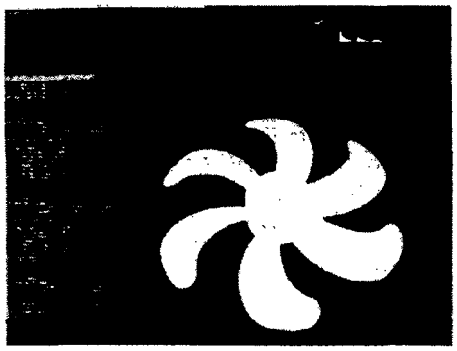
The rapid tool manufacturing project combines expertise in robotics, mechanical, metallurgical, and computer engineering to reduce product development costs and time. Viewed from a systems perspective, the problem involves rethinking many manufacturing activites from the initial design process onward. Working elbow-to-elbow with the EDRC research team for two years has been a joint state-industrial consortium whose members supplied materials, expertise and experience while learning, testing, and implementing new technology. Consortium members included: the Edison Materials Technology Center of Ohio (EMTEC); General Motors' Packard Electric, Delco Electronics, and Inland Fisher Guide divisions; ALCOA; Ford Motor; and Goodyear.

Tooling manufacture is typically an expensive and time-consuming process. This is due not only to fabrication costs and time constraints imposed by conventional machining methods but also to the fragmented nature of industrial organizations. In most organizations, the representations and processes used to design and manufacture tools and products vary from one group to another. Expertise in tool design and product design also may reside in separate groups. As a result, the representational and physical models used in design, prototyping, and manufacturing are often incompatible and cause delays and errors in the transitions between stages. Products often make several complete cycles through design, prototyping, and fabrication before reaching production. Thus, new product development or product modification implies a series of iterative changes for both product manufacturers and tool makers. The seamless transition from product concept to production remains a serious bottleneck in increasing productivity.

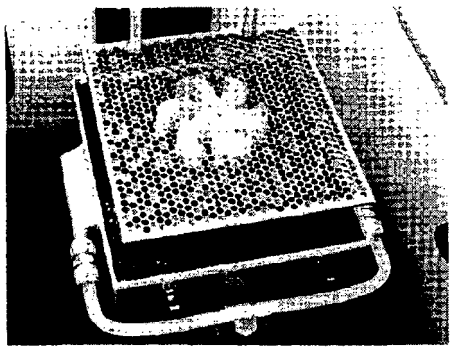
The rapid tool manufacturing project combines the EDRC geometric modeler Noodles with existing fabrication technologies to produce a rapid tooling process capable of reducing the time and cost of manufacturing custom tooling by nearly an order of magnitude. The process moves from design through prototype to fabrication of a tool for an injection molded part in three basic steps: CAD modeling, stereolithography, and thermal spray deposition. This progression is illustrated in photographs in Fig. 6.

The unified representation underlying the CAD/CAM component of the rapid prototyping manufacture system, called Noodles [23], provides a single environment for design, analysis, and reasoning about solid objects in one, two, and three dimensions. For design, it provides paradigms for interactive model creation and linkage to relational databases for nongeometric information. For analysis, it performs finite-element mesh generation for performance analysis and supports manufacturability analyses. For reasoning, it handles shape abstraction and feature recognition. A Noodles representation of a part is shown in Fig. 6(a).

A variety of shape deposition processes can produce three-dimensional shapes by building incremental thin layers of material. These include: selective laser sintering, laminated object manufacturing, ballistic powder metallurgy, three-dimensional printing, stereolithography, and near-net thermal spraying [24]. For this project, EDRC researchers elected to use stereolithography and arc spray equipment. Stereolithography creates plastic prototype models directly from a vat of liquid photocurable polymer by selectively solidifying layers with a scanning laser beam [25]. Fig. 6(b) shows the SLA part created from the Noodles representation. In arc spraying, metal wire is melted in an electric arc, then atomized and sprayed onto a substrate surface. On contact, the sprayed material solidifies and forms a surface coating. Spray coatings can be built up by depositing multiple-fused layers that, when separated from the substrate, form a free-standing shell with the shape of the substrate surface. By mounting the shell in a frame and backing it up with appropriate materials, a broad range of tooling can be fabricated, including injection molds, forming dies, and electrodischarge machining (EDM) electrodes. The next step in the CAD/CAM approach is automating the thermal spray process using robots. Fig. 6(c) demonstrates the robotic spraying technique [26]. Converting from man-



(a)



(b)

(c)

Fig. 6. A rapid tooling process: geometric model of a part created using Noodles; three-dimensional rendition of part using stereolithography; robotic spraying of zinc to create one-half of die mold; and completed die molds.

ual to robotic spraying driven by an off-line trajectory and process planner renders more consistent tooling quality and provides more predictable performance of the sprayed metal shell. The end product of a prototype injection molded part is shown in Fig. 6(d).

Integrating spraying and stereolithography within a unified CAD/CAM environment reduces the number of iterative cycles in the stages of design, prototyping, and fabrication. CAD-based evaluation and modification tools can operate on design models to help the designer create

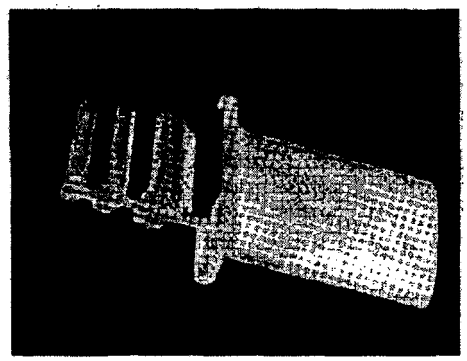


Fig. 7. Turbine blade produced by robotic spraying of steel layers onto a mask created by CO2 laser.

manufacturable designs based on the requirements and limitations of the downstream processes. For example, a design critic can identify shape features that are difficult to spray so that the designer may modify them before reaching the fabrication stage.

As part of this collaborative research effort, GM's Inland Fisher Guide Division has adopted the Noodles polygonizer interface, an application in the Noodles toolkit, to drive its stereolithography apparatus. This technology has provided GM the unique capability to transform part data from surface-based representation to solid models, thus linking stereolithography with GM's CAD/CAM system. As a result, GM has been able to dramatically increase the number of pieces, or duplicate prototype parts, relative to the number of prototype parts it produces. This improvement has increased the chance of catching costly design errors in a timely manner by satisfying the growing demand for evaluation by diverse design, engineering, and manufacturing groups within the corporation before proceeding to mass production.

The rapid tooling consortium has further motivated the development of MD*, a recursive masking and deposition system. In this process, a laser first cuts a mask out of paper, which is then sprayed with metal. EDRC researchers can thus create parts directly from the Noodles geometric modeler much faster and at a fraction of the usual cost. A sample part is shown in Fig. 7. The proposed process would enable designers to realize geometries inconceivable using conventional manufacturing technology. This technology has the potential to create functional assemblies, such as linkage mechanisms, and eventually full assemblies such as engines and computers, without any parts assembly.

### *B. Case Study #2: Layout Design*

EDRC research in layout design illustrates a sequential cross-disciplinary progression that was motivated by an industrial partner. This effort began in the domain of architecture, was expanded to integrated building design, and then was applied to analog computer board layout in a collaborative effort with the Digital Equipment Corporation.

Layout design tackles many complex issues that typically arise in the design of artifacts that must satisfy spatial and functional constraints. A potentially infinite number of location and orientation combinations are available for placing any single object. In each combination design objects interact through their shapes, sizes, and their spatial or topological relations. Layout design decisions must simultaneously satisfy global requirements (e.g., use of space) and local requirements (e.g., adjacencies between pairs of objects). An acceptable spatial arrangement often exhibits a complex pattern of trade-offs. For these reasons, an exploration of the structure of the layout task and a search for candidate solutions is required. Due to cognitive limitations, human designers have limited capability for making systematic explorations of alternative arrangements. This shortcoming in human performance has motivated numerous attempts to apply computational methods to layout. What is desired is a structured method for producing alternatives, each of which embodies trade-offs that can be understood and justified.

The LOOS layout synthesis system [27] was developed in response to the challenges of the layout task. Initially motivated by architectural layout, the LOOS system systematically generates layout alternatives and evaluates them against multiple performance criteria. It uses a graph-based representation that separates topological issues (spatial relations between objects) from metrical issues (dimensions and dimensional positions of objects) in layout. The representation uses the basic spatial relations *above, below, to the right of*, and *to the left of* to define the topology of a layout as a set of relations between pairs of rectangles. Using this representation, a small set of rules or operations can generate all possible arrangements of rectangles in a plane by inserting one rectangle at a time. The layouts produced by LOOS are loosely packed arrangements of rectangles; that is, the rectangles are pairwise nonoverlapping, but need not fill a surrounding rectangle. These rectangular arrangements are given meaning as layouts in a particular domain by attributing the layout objects or components from the domain to respective rectangles. Performance requirements for the layout are attached to these objects, enabling the layouts produced to be compared and evaluated. Those failing requirements may be discarded, while those showing promise can be further developed. A key feature of LOOS is that the domain-independent generation of layouts is separated from the domain-specific tester that applies evaluation criteria to the partial configurations generated. The generate-and-test design strategy has enabled LOOS to produce quality solutions for small but realistic layout problems.

The second-generation system, ABLOOS (abstraction-based LOOS) [28], builds on the LOOS system by increasing the size of feasible layout tasks and the system's applicability across domains. ABLOOS allows a layout task to be hierarchically decomposed into subtasks using goal-objects (GOB's). Each GOB represents a layout problem at a specific level of abstraction. The layout subtasks are then solved and recomposed to achieve an overall solution.

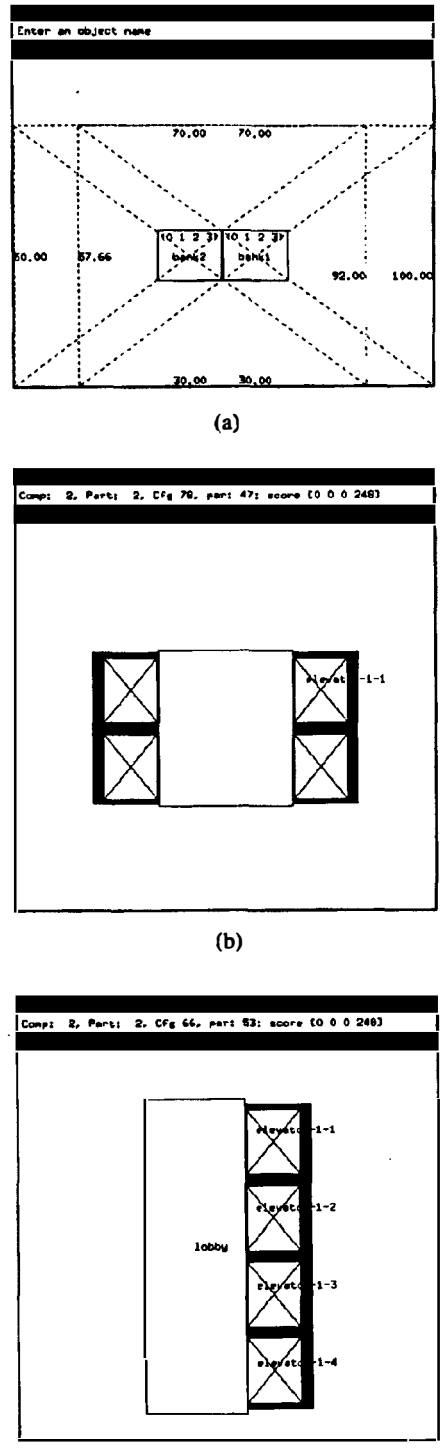
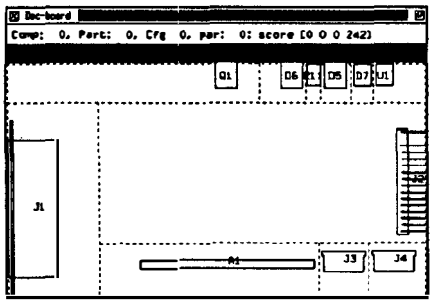
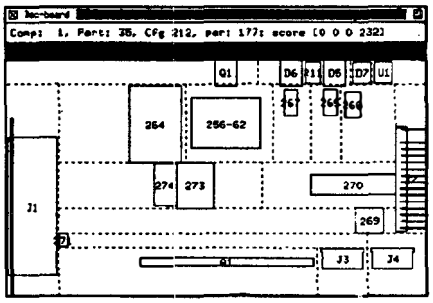



Fig. 8. Initial application of ABLOOS to architectural layout of a building core: (a) initial layout of elevator banks based on two goal-objects; (b) alternate placement after insertion of a third goal-object: a lobby; and (c) alternate placement after insertion of lobby.



(a)



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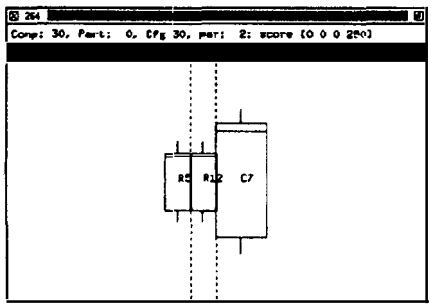

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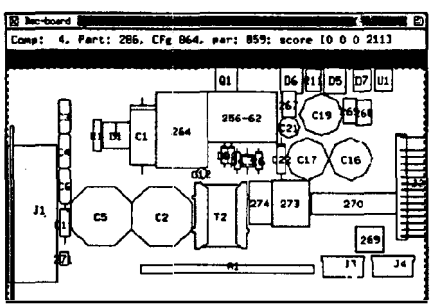
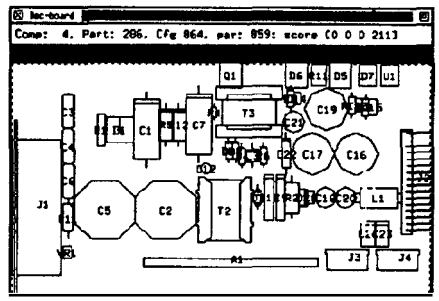


(d)

Fig. 9. Extension of ABLOOS to layout of analog computer board supplied by Digital Equipment Corp.: (a) insertion of preplaced components; (b) insertion of goal objects 256 and 274; (c) expansion of goal object 264; (d) one feasible layout in terms of goal objects; (e) feasible layout with all goal objects expanded; (f) an alternate layout given horizontal component alignment.



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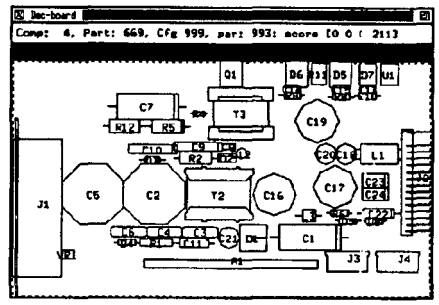

(f)

Fig. 9. contd.

The application of ABLOOS to the architectural layout problem of configuring elevator banks, lobbies, etc. in the vertical circulation core of a building is illustrated in Fig. 8. The status after two abstract GOB's is shown in Fig. 8(a). In this case the elevator banks have been placed; the two dashed rectangles represent the slacks within which the GOB's may be located or shaped without affecting the spatial constraints. Two alternate arrangements after the next GOB, the lobby, has been inserted are shown in Fig. 8(a) and 8(b).

The use of ABLOOS in the industrial problem of analog computer board layout involving 60 components with multiple placement constraints is shown in Fig. 9. In Fig. 9(a) the preplaced components (pins, etc.) have been entered. In Fig. 9(b), abstract GOB's 256–274 have been inserted (the dashed lines represent the channels which separate the GOB's and through which connections can eventually be routed). In Fig. 9(c), GOB 264 is expanded into its constituent elementary components. A feasible layout is shown in Fig. 9(d) in terms of GOBS and in Fig. 9(e) with all GOB's expanded. An alternate layout, where the preferred component alignment axis is horizontal, is shown in Fig. 9(f).

Expanded and generalized across domains, ABLOOS now provides a flexible, hierarchical and interactive toolkit for layout design. The toolkit comprises operations or rules to generate layouts; propagate dimensional constraints; and remove, reinsert, aggregate, disaggregate, and evaluate objects in terms of multiple constraints. The rules depend on a formal graph-based relational representation. The design

Fig. 10. Vu-Man: a wearable computer incorporating a commercial heads-up display unit.

process relies on a human-computer partnership in which the computer enumerates a space of alternative designs and rapidly evaluates the alternatives, while the human designer creates the evaluation rules and an appropriate decomposition for a given task. Rules may be flexibly combined to yield a variety of powerful methods for layout design ranging from systematic and exhaustive enumeration of alternatives to incremental interactive design, editing of nearly correct layouts, and redesign. The system has performed both stacked layouts in 2.5-D space and true 3-D arrangements.

ABLOOS is currently being extended to the two domains of plant layout and computer board and chip layout. Research is underway to incorporate mathematical programming and combinatorial optimization methods into the framework. ABLOOS is also being used as a testbed to investigate methods of capturing knowledge, building design repositories, and learning within engineering design environments. As a direct consequence, the original motivating domain, architectural layout design, has itself been vastly enriched.

In a 1991 summer EDRC course for industry, ABLOOS and Noodles, together with MICON [29], a computer synthesis system, and other EDRC tools, were used concurrently in the "hands-on" design and fabrication of a new product idea, called Vu-Man, a wearable computer that incorporates a commercial "heads-up" display unit (shown in Fig. 10). This effort combined expertise in electrical, computer, and mechanical engineering with architecture and industrial design in the Center's first attempt to create a novel product idea based on the concurrent implementation of new design methodologies.

## VI. Summary

The establishment of an Engineering Research Center in design at Carnegie Mellon University in 1986 was a logical event in the institution's historical development because cross-disciplinarity and the industrial perspective have been themes in both its design education and research for half a century. The concern with disciplinary balance in the academic curriculum can be traced back to the introduction of the Carnegie Plan in 1935. This program originated the liberal-professional ideal of integrating technical and liberal arts courses in an innovative curriculum for engineering and science students. A major component of the plan combined emphasis on analysis and design in engineering in a sequence of ASE (analysis, synthesis, and evaluation) courses in which students applied material learned from analysis courses to challenging, open-ended design problems in interdisciplinary group projects "in which the student experiences the responsibility of leadership and teamwork" [30]. The academic administrators responsible for implementing the plan came to the institution from the General Electric Corporation.

Over thirty years after the introduction of the Carnegie Plan in the academic curriculum, Herbert Simon's *The Sciences of the Artificial* [31] presented a vision of design as a deservedly rigorous and teachable discipline. The book inspired a small group of faculty in engineering, computer science, and architecture to attempt to develop a framework for design research and education using computational techniques. In 1974 this informal group formed the Design Research Center (DRC), a meeting ground for faculty exploring Simon's vision of design and mounting industrial projects for immersion in industrial design problems.

The dual traditions of cross-disciplinarity and industrial collaboration thus formed the basis for Carnegie Mellon's response to the creation of the NSF Engineering Research Centers. EDRC provided the opportunity to generate a unified long-term vision for cross-disciplinary design research focused on competitive need. The critical importance of competitiveness in effect charges EDRC with reducing not only the product development cycle but also the knowledge development cycle that begins with theory and extends to education, industrial practice, and new products.

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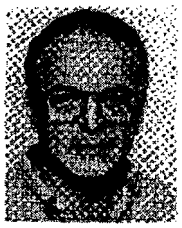

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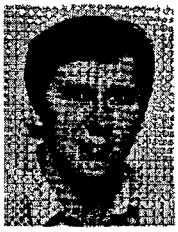

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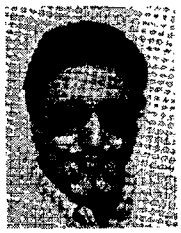

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Main research interests: design theory, design oriented organization, design and neurosciences, design economics, design and creation, design history.

**Title of the Presentation:**

Introduction to C-K design Theory

**Synopsis:**

We first present the basic 'requirements' for a contemporary design theory. We analyze the basic notions of the theory (C-space, K-space, expansive partition…). Then we show how C-K design theory extends other design theories studied in the previous basic courses (Simonian tradition, German systematic). We conclude with some implications of C-K design theory.

**Main References:**

Hatchuel, A., and Weil, B. (2003) "A new approach to innovative design: an introduction to C-K theory." ICED'03, August 2003, Stockholm, Sweden, 14.

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**Further readings:**

See references in "Chapter 4" above.

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# A NEW APPROACH OF INNOVATIVE DESIGN: AN INTRODUCTION TO C-K THEORY

Armand Hatchuel and Benoît Weil

## Abstract

In this paper we introduce the main notions and first applications of a unified design theory. We call it "C-K theory" because it stands that a formal distinction between spaces of "Concepts" (C) and space of "Knowledge" (K) is a condition for design. This distinction has key properties: i) it identifies the oddness of "Design" when compared to problem solving approaches ; ii) it distinguishes C-K theory from existing design theories like German systematic as C-K theory offers a precise definition of design and builds creativity within such definition. It does not require the too restrictive assumptions of General Design Theory [1] or Universal Design Theory [2]. It establishes that design reasoning is linked to a fundamental issue in set theory: the "choice" axiom. It models the dynamics of design as a joint-expansion of a space of concepts and a space of Knowledge needing four operators C→K, K→C, C→C, K→K. They compose what can be imaged as a "design square". These operators capture the variety of design situations and the dynamics of innovative design.

*Key worlds : design theory, innovation, creativity.*

## 1. Introduction. Why a new design theory ?

In this paper we present the main notions of a unified design theory. We call it "C-K theory" because its central proposition is a formal distinction between "Concepts" (C) and "Knowledge" (K). Design theories have been extensively discussed in the literature. So, what could be the claims of this new theory? What kind of improvement can C-K theory provide in design practice? In this paper we shall focus only on the theoretical aspects of C-K theory even if C-K theory was born from practical design issues in highly innovative contexts and is now used in numerous and well known innovative firms [3].This paper presents the basic elements of C-K theory and attempts to establish its validity and utility. Before, we will give an overview of the origins of C-K theory and of the main issues it wants to address.

C-K theory bears upon existing design theories, yet it re-interprets these theories as special cases of a unified model of reasoning. This model allows to solve two recurrent problems faced unsuccessfully by traditional theories:

- **to offer a clear and precise definition of "design":** this definition should be independent of any domain and professional tradition. It should give to "design theory" the same level of rigour and modelling that we find in decision theory or programming theory. This means that design theory should have robust theoretical roots linked to well recognized issues in logic. Design is one of the most fascinating activities of the mind, it would be surprising that a design theory had no relations

with the foundational problems in logic or rationality that have been explored during the 20th century. We show below how C-K theory establishes such an important link.

- **to offer a theory where creative thinking and innovation are not external to design theory but are part of its central core**. This is a logical necessity: Design is a process by which something unknown can intentionally emerge from what is known. Usually this process seems contradictory with a well structured theory. The more a Design theory is rigorous and precise, the more it seems to exclude creativity and imagination. Yet, C-K theory aims to reconcile these two goals.

In the first part of the paper we briefly review existing theories and there ability to meet these issues. In the second part, we present the main notions of C-K theory. In the third part we begin to discuss the validation criteria for C-K theory, in particular we discuss the unifying power of C-K theory and how it is possible to interpret creativity with C-K theory in a new perspective.

# 2. Design theories: a short critical review

In this paper, our focus is the improvement of the type of Design theories which present a formal structure. We mean by "formal", the description of Design activity as a specific *form of reasoning* or rationality. The formal language used could be mathematical, meta-mathematical, computer oriented or simply taxonomic. The aim is to establish a model of thought [4] that defines design and offers constructive principles for designing. Yet, to identify more precisely the scientific background of this program a preliminary remark is necessary.

## 2.1. Design theories and the social shaping of design : the case of R&D.

For sure, Design is not only a mode of reasoning. It is also a human collective process shaped by history, culture, and social or organizational norms. *Yet, these two perspectives on design are not independent.* For instance, if Design is dominantly described as a three stages process (like in the German systematic), such formal scheme can be used as a work division norm, which finally shapes roles, skills and social identities. However, the distinction between architects and engineers is not only the result of different design theories, it is the legacy of a historical and social process that shaped two skills with different schools, cultures and professional organizations.

A comprehensive view of design should address both aspects. But, in this paper it is not our goal to offer such encompassing view[1]. However, it is worth mentioning one particular critical organizational issue that is supported by our approach (i.e. by C-K theory). The Design literature tends to accept the classic concept of R&D [2]. In this view, Research departments or Science labs are not perceived as design workshops or are not concerned by design theory. Research is described as creating new knowledge without any design purpose. This approach is valid only in special cases. Moreover a *design project can include scientific research work,* and we stand that the creation of new knowledge is a logical necessity in any design process ! Empirically, this is observable in many science-based industries like the pharmaceutical ones. In C-K theory it is a logical consequence as "knowledge expansion" (i.e. Research) is a primary axiom of Design

[1] We have discussed elsewhere the contemporary evolution of organizational principles for design in several companies [3].

reasoning. Therefore, C-K theory predicts the necessity of organisations where Research is not separated from Development or where new links between R and D have to be identified and implemented [3].

## 2.2. A short survey of design theories: Process and mapping theories.

The multiplicity of design theories offered in the literature is well known. A good survey of this variety is a difficult task. Moreover a clear synthesis of these theories is limited by the use of confusing or very similar notions. In a large survey, the authors [5] remarked that the existing definitions of design reflects such a variety of view points that they could only list key words: «*Needs, requirement, solutions, specifications, creativity, constraints, scientific principles, technical information, functions, mapping, transformation, manufacture, and economics*". This seems a realistic description of the state of the art. Therefore, we are left with the unique option to depict the main logics of these design theories. It has been already noticed that existing Design theories are either *process* or *product* oriented [5], [6]. We will keep this distinction for a brief critical review.

- **Process, stages and the recursive nature of design**: Process oriented design theories define design *stages* that have to be followed in order to achieve a design task. Thus the value and validity of such theories depend on the definition they offer about such stages.

The well known German systematic model [7] distinguishes three stages for any design process: the functional, conceptual, and embodiment design stages. Unfortunately, these levels often overlap. For example, it is not easy to formulate a functional property without already using a conceptual model. If we say that we want "to know what time is it ?": obviously the function (know the time) is already expressed through the conceptual notion of "time" as a measurable phenomena and this largely determines the conceptual design that will follow. In the German approach, the three stages are only *a heuristic* proposition, that can be useful in many engineering cases. So, are there universal stages in a Design process ? Watts [8] assumed levels of abstraction or concreteness and Marples [9] defined stages resulting from a decomposition of the main design problem in ad hoc sub-problems. These are not universal but contingent stages (and we will argue later against this idea of "decomposition").

Nevertheless, the idea of "stages", even if there are no universal stages in Design, outlines an important point. Design reasoning has the property of **recursivity**. Design does not only transform projects into solutions, but also *projects into projects*, or design problems into design problems. What could therefore be the end of a design process ? The usual answer is a "satisficing" solution [10]. But what proves that we can reach one ? Some authors solve the problem by setting axiomatically that a design problem has a finite number of stages [2]. Usually, it is said that Design stops when the designer "meets" the specifications of the problem. Yet this means that specifications are propositions that can be "met": but how ? What is the accepted tolerance about such "meeting" ? All process oriented theories have to clarify what is viewed as "an end" of the design process.

Finally, process oriented theories which do not specify a prescriptive definition of stages, are very close to standard Problem solving theory as defined by Herbert Simon. And Simon always claimed that "*design theory was nothing else than problem solving theory"* [11]. In his view, "Finding a problem space", "using search processes to generate alternatives", "adopting satisficing criteria" were the common components of both design theory and problem solving theory. This view has a

major disadvantage: Design is no more *distinguishable* from other problem solving situations. Simon recognized the issue and repeatedly attempted to integrate creative thinking within problem solving theory. Hatchuel have argued [12] that this effort was an impossible one, as creativity cannot be just "added" to problem solving theory, it has to be built in the definition of the process. We will see that contrary to Simon's view, C-K theory leads to consider problem solving theory as a special and restricted case of Design theory.

- **Product oriented Design theory and "mapping" theories as specification theories.** All Product-oriented design theories are based on some specific properties explicitly required from the product to be designed. Therefore, product based theories are in fact *specification theories.* Suh axiomatic [13] is a good example of a specification theory that calls itself a design theory. Suh defines axiomatically two universal product attributes. These specifications only form new functional requirements that could be added to the primary functional requirements used to built the Suh's matrix. The same could be said from other theories [14]. Evolutionary design [15] is an interesting attempt to mix process and product but it is basically a problem solving theory where problems are discovered progressively.

- **An interesting proposal: General design theory and its biased view of the knowledge process** [1], [16]. This theory deserves a special discussion. It is an attempt to build a rigorous and universal theory of design as "a mapping between the function space and the attribute space". Yet, all the modelling effort is concentrated on structuring the functions space and the attribute space so that a "good" mapping is always possible in situations of "ideal knowledge": i.e. situations where "all is known about the entities of a product domain". The paradox is that Yoshikawa defines as ideal, a situation where Design disappears. If we perfectly know the functions, the attributes and how to fit functions and attributes, what is left for design ? To sum up, in a perfectly and totally known domain there is nor design, nor designers. Yoshikawa recognized the issue and also studied "real knowledge" situations. In this second case, his model leads to interesting results: one of them called theorem 32, is noteworthy: "In the real knowledge a design solution has unexpected functions". This is a an interesting way to underline a fundamental property of design: *design cannot be defined without a simultaneous knowledge "expansion" process.* As "discovering unexpected functions" means obviously acquiring new knowledge. Yet, it is not a free learning process per se as it is embedded and oriented by the design process. However, Yoshikawa does not derive all the consequences of this result for a more complete definition of design: define the link between concepts and knowledge as the core issue of design and reject the concept of design in the world of "ideal knowledge" as misleading. Instead, he simply suggests that, within the "real knowledge world", Design is a heuristic process built upon a "refinement model" [16].

This is certainly a too short survey of existing theories and we may have forgotten some important proposal. Yet the difficulties of surveying Design theories is a good signal of the present advancement of field. At least, our survey indicates that improvements in Design theory should be obtained in three directions:

- Defining design as a form of reasoning where creativity is built-in its definition
- Defining design as a process where knowledge expansion is built-in its definition
- Defining design as a process whose output could be a new design issue.

In the following section we present the main assumptions of C-K theory which meets in our view these requisites and offers a wide variety of results.

# 3. The principles of Concept-Knowledge theory (C-K theory)

C-K theory has been initially proposed by Hatchuel [17] and developed by Hatchuel and Weil [18], [19]. The theory is based on the following interdependent propositions that will be presented here in the case of *an individual designer*. But the theory can be extended for collective design.

## 3.1. Assumptions and Definition of Design

1. We call K, a "knowledge space", the space of propositions that have a logical status for a designer D. This space is always neglected in the literature, yet it is impossible to define design without such referring space.
2. We call **"logical status of a proposition", an attribute that defines the degree of confidence that D assigns to a proposition**. In standard logic, propositions are "true or false". In non standard logic, propositions may be "true, false, or undecidable" or have a fuzzy value. A Designer D may use several logics . What matters in our approach is that we assume that **all propositions of K have a logical status what ever it is**, and we include here as a logical status all non-standard logical systems. In the following, we will assume for simplicity reasons that in K we have a classic "true or false" logic. But the theory holds independently of the logic retained.
3. We call **"concept", a proposition, or a group of propositions that have no logical status in K.** This means that when a concept is formulated it is **impossible to prove** that it is a proposition of K. In Design, a concept usually expresses a group of properties qualifying one or several entities. If there is no "concept" Design is reduced to past knowledge[2].
4. **Definition 1 of Design:** assuming a space of concepts C and a space of knowledge K**,** we define Design as the process by which a concept generates other concepts or is transformed into knowledge, i.e. propositions in K**.**

**Comment 1**: This definition clarifies the oddness of Design reasoning. There is no design if there are no "concepts": concepts are candidates to be transformed into propositions of K but are not themselves elements of K. If we say that we want to design "Something having the properties (or functions) $F_1,F_2,F_3,\ldots$": we are necessarily saying that the proposition "Something having the properties $F_1,F_2,F_3$" is nor true nor false in K. **Proof:** If the proposition was true in K it would mean that this entity already exists and that we know all that we need about it (including its feasibility) to assess the required properties. Design would immediately stop! If the proposition was false in K the design would also stop for the opposite reason. It is important to remark that there is no concept per se but relatively to K. We call it the **K-relativity** of a design process. This definition captures the very nature of design and have important operational consequences.

[2] This distinction between C and K is essential to our definition of design. Even if we admit in K a very weak form of logic this distinction should be maintained. A design concept is a proposition that can't be logically valued in all logics assumed in K. Such strong axiom is a condition that avoids to reduce design to classic problem solving. If it was possible to give any logical status (L) to the concept this would mean that the proposition ("it exists an entity having properties $P_1$, $P_2$, $P_3$,.." have the status L) is a true proposition in K. This would open the way to several contradictions and probably to some circularity similar to Godel's classic incompleteness theorem.

**Comment 2**: traditionally design is defined by the intention to fulfill some requirements, or as a proposal to fulfill some requirements [5]. These notions have a practical meaning when for instance some client formulates a requirement and a designer answers by a proposal. In our framework the formulation of the "requirements" is a first concept formulation which is expanded by the designer in a second concept that is called the proposal.. The latter being a new design departure for the designer or for other design actors. Moreover, in our theory the logic of "intention" is built-in the definition of a concept. What would mean the intention to design if it concerns something that is already completely defined in K? We can even characterise the broad world "intention" in design as a class of endeavours or deeds that aim to bring a concept to some form of "reality" i.e. logical status in K.

As required earlier, **creativity is now clearly built-in the definition of Design**. A concept being nor true nor false, the design process aims to transform this concept and will necessarily *transform K*. All classical definitions of Design are special cases of our definition. If we say that we have to design a product P meeting some specifications S, we are implicitly saying that the proposition (Product having property S ) is a concept ! But usually one forgets to indicate to which K should one refer a design problem. If we want to design a "flying bicycle", we formulate a concept relatively to the knowledge space available to almost everybody. But if we say a "flying boat", then it's a concept only for those who never heard about hydroplanes ! **K-relativity** is central for understanding how Design is shaped by different traditions. A "ready made artistic work" was a concept for Marcel Duchamp [20], a founder of modern art, but it was a false proposition for classic Art.

## 3.2. Space of Concepts, concept-sets and concept expansion: a new interpretation of the choice axiom in set theory.

Now that we have a well formed definition of Design, we can derive from it the process of designing. We need before other definitions of what we call a "concept-set" and "concept expansion". This is a crucial part of the theory and we will follow a step by step presentation.

1. **Concepts as specific Sets**: as said before, a "concept" C is a proposition which has no logical status in a space K (i.e. nor false nor true in K). It says that "an entity (or group of entities) verifies a group of properties P". This definition is equivalent to defining a set associated with C. This set will be called also C: it contains all entities that are partly defined by P. Yoshikawa [1,21], uses a similar notion called entity-concept. However our assumptions about this concept-set are quite contrary to his[3]. His concept-set aims to capture all the

[3] The Yoshikawa's. "set concept" or "entity concept" or "concept of entity" is the set that contains all the objects of a domain. This allows him to formulate theorem 5: "the entity concept in the ideal Knowledge is a design solution". This means that there is no disjunction between existing knowledge and the entity concept. In his model of real knowledge Yoshikawa has therefore difficulties to define his entity concept as it becomes impossible to say that the concept contains only design solutions. Lets take an example if we want to design "a flying boat" in the Yoshikawa's approach of an entity the design solution will have to be a boat in exactly the same definition than in the original set. This is precisely what we avoid in our definition of a concept. The design of "a flying boat" could possibly be an object which could not be defined as a boat in the first phase of the design project. This is also why the choice axiom in C is rejected. An other indication of the difference between our approach and Yoshikawa's one can be seen in his hypothesis that the entity concept can be associated to a functions space containing all the classes of the entity concept. This means that the power set of the concept set is also perfectly known. This is also contradictory to our rejection of the choice axiom.

existing objects of a domain and this is, in our view, in contradiction with the definition of design. Therefore, due to our definition of Design, C has the following strange property!

2. **Concepts are sets from which we cannot extract one element !** Why such a strange property ? If we say that we can always extract one entity from the concept-set, then we are in contradiction with our proposition that a concept has no logical status in K. **Proof:** if we could extract one of these entities, it would mean that the concept is true for this entity; hence it wouldn't be a concept but a proposition of K ! Yet, why not consider all those entities except this one ? This means that we change the first concept by a new required property (be different from the already existing entity). Now, the new concept also should show no element we can extract, otherwise we would repeat the same process ! Finally, being a concept impedes the possibility to have elements that can be isolated ! **This property of concept-sets corresponds to a well known issue in Set theory: the rejection of the axiom of choice axiom .**
3. **Proposition: In design, concepts are sets defined in Set theory without the "choice axiom":** The importance of the choice axiom in Set theory is paramount [22]**.** The choice axiom says that it is always possible to "find" an element of a set, and accepting or rejecting the choice axiom controls the nature of mathematics. *Our definition of Design appears now deeply rooted in the foundational issues of mathematics*. Design needs concepts and concepts are sets where we cannot accept the choice axiom. And yet, concepts are still sets ! We know from a famous theorem due to Paul Cohen in 1965 [22] that the choice axiom is independent from the other axioms of Set theory: **This means that while rejecting the choice axiom we can still use all basic properties and operations of sets for concepts!** [4]
4. **Concepts-sets can only be partitioned or included, not "searched" or "explored"**: the practical consequence of rejecting the choice axiom is immediate: we cannot "explore" the concept or "search" in such sets ! **Proof**: how could we do that, if it's impossible to extract one element ! The metaphors of "exploration" or "search" are thus confusing for design. This explains why empirical studies are so embarrassed to find the "search processes" they look for in design activities [23]. Now, if we cannot search a concept what can we do *? We can only create new concepts (new sets) by adding or substracting new properties to the initial ones*. If we add new properties we partition the set in subsets; if we subtract properties we include the set in a set that contains it. Nothing else can be done in space C, but this is enough to reach new concepts.
5. **By adding or subtracting properties we can change the status of concepts. Proof:** Each time we make an operation like these, we may generate a new proposition of K. Let us consider "bicycles with pedals and effective wings" as a concept (relatively to our Knowledge space). If we subtract the property "have effective wings", we obtain "bicycles with pedals" which for almost all of us is not a concept but a true proposition (hence belongs to K) ! The reverse transformation is a partition of "bicycles with pedals" into two concept-sets: "bicycles

[4] One may thinks that by rejecting the choice axiom any set operation on C will be refused. This is not the case. What is forbidden is the possibility to extract or find **one** element of C, but all others operations on sets are still possible. That is why there is a complete branch of set theory that is still possible without choice axiom [22]. Usually the choice axiom is famous for creating celebrated paradoxes like the Banach-Tarski paradox where one sphere can be divided in pieces that allow to make two new identical spheres. Such paradoxes are obtain not when sets are manipulated through there properties, but only when a single element is supposed to be found in the manipulated set.

with pedals and effective wings" and "bicycles with pedals and no effective wings". The former is now a concept for those (including the authors) who never saw "flying bicycles" (different from "flying motorcycles" which already exist) and cannot say if they will ever exist. **These elementary operations are all what we need to define at a high level of generality the process of design** !

## 3.3. Disjunctions and conjunctions: The dual dynamics of design

The process of adding and subtracting properties to concepts or propositions is one **central mechanism of Design**: it can transform propositions of K into concepts of C and conversely. Let us define more precisely these processes.

1. We call "**disjunction"** an operation which transforms propositions of K into concepts (going from K→ C); and we call "**conjunction"** the reverse operation (going from C→K).
2. What usually appears as a design solution is precisely what we call a "**conjunction"**. What does that mean? It means that we have reach a concept which is characterised by a sufficient number of propositions that can be established as true or false in K. This also means that we have now reached a definition of an entity which takes into account all existing knowledge and fulfills a series of properties clearly related to the initial concept. This is precisely a good "definition" of the entity that we wanted to design. And defining the object we want to design is equivalent to saying that we have designed it!. Another important remark is that this definition is still associated to a set of entities in K but we can now accept the choice axiom in this set . **Finally in our theory designing a concept is transforming a set where the axiom of choice is rejected into a set where it is accepted**. Yet this last set exists only in K. Why do we need the choice axiom here? Precisely to be able to speak of **one** solution, but it is possible to assume that design never ends in one solution but in a set-solution in K: the classic idea of geometrical tolerance in mechanical design is exactly the same idea. We never design one geometrical object but a set of geometric objects defined by the interval tolerance.
3. **Definition 2**: Design is the process by which K→C disjunctions are generated, then expanded by partition or inclusion into C→ K conjunctions.
4. **Proposition: the space of concepts has a tree based structure: Proof:** A space of concepts is necessarily tree-structured as the only operations allowed are partitions and inclusions and we have to assume at least one initial disjunction (this a classic result in graph theory). Several Design theories has used the tree structure to represent design reasoning [9] but they misinterpreted it as a decomposition process. A tree structure appears because we can only add or subtract properties. Yet adding properties to a concept seems to decompose a concept into sub-concepts: this is an illusion, as in design the tree is necessarily an "expansion" of the concept. To understand this point we need to distinguish between two type of partitions: respectively, **restricting and expanding partitions.**
5. **Definition of restricting and expanding partitions:** If the property we add to a concept is already known (in K) as a property of the entities concerned, we call it a **restricting partition**; if the property we add is not known in K as a property of the entities concerned, we have an **expanding partition**. In other words, restricting means detailing the description with already known attributes, while expanding means adding a new topology of attribute.

   **Example**: If we design a "system for stopping a car in case of extreme danger», we are not going to partition this set with known properties of "car brakes", we need to expand the concept

by allowing new properties of the brakes or of the engine. The necessity of expanding partitions in Design explains why Yoshikawa (Yoshikawa 1981) finds "unexpected functions" for a "solution" but he misses the deep importance of this result in the definition of the design process itself.

6. **Creativity and innovation are due to expanding partitions of concepts:** This also reveals why creativity is built in our definition of design: concepts can be freely expanded provided we have available expanding properties. But where do these properties come from ? The unique answer is from K ! And this shows how the unknown comes from what is already known provided we accept the concept as a vehicle !

Now we have all the components needed to present C-K theory as a unified Design theory.

## 2.4. The four C-K operators and the "design square"

All preceding propositions define Design as a process generating **the co-expansion of two spaces**: spaces of concepts C and spaces of knowledge. Without the distinction between the expansions of C and K, Design disappears or is reduced to mere computation or optimisation. Thus, the design process is enacted by the operators that allow these two spaces to co-expand. Each space helping the other to expand. This highlights the necessity of four different operators to establish the whole process. Two can be called "external": from C→K and from K→C; and two are "internal": from C→C and from K→K. Let us give some indications on each operators. The four operators form what we call *the design square.* A complete study of these operators is beyond the scope of this introductory paper.

1. **The external operators**:
   - **K→C**: This operator adds or subtracts to concepts in C some properties coming from K. It creates "disjunctions" when it transforms elements from K into a concept. This also corresponds to what is usually called the "generation of alternatives". Yet, concepts are not alternatives but potential "seeds" for alternatives. This operator expands the space C with elements coming from K.
   - **C→K**: this operator seeks for properties in K that could be added or substracted to reach propositions with a logical status; it creates conjunctions which could be accepted as "finished designs" (a K-relative qualification). Practically, it corresponds to validation tools or methods in classical design: consulting an expert, doing a test, an experimental plan, a prototype, a mock-up are common examples of C→K operators. They expand the available knowledge in K while being triggered by the concept expansion in C.
2. **The internal operators:**
   - **C→C**: this operator is at least the classical rules in set theory that control partition or inclusion. But it can be enriched if necessary by consistency rules in C.
   - **K→K**: this operator is at least the classical rules of logic and propositional calculus that allow a knowledge space to have a self- expansion (proving new theorems).
3. **The design square, and C-K dynamics**

Figure 1 combines the four types of operators in what can be called the "**Design square**". It gives the fundamental structure of the design process. It also illustrates the importance of defining Design both on concepts and knowledge. This model avoids the classical logic of design stages from

"abstract to concrete" or from "rough to detail". These are too normative positions: "details" may come first in a design if they have a strong partitioning power ;.and unexpected stages could result from a surprising knowledge expansion. The classical opposition between linearity and turbulence disappears: innovations could result from both.

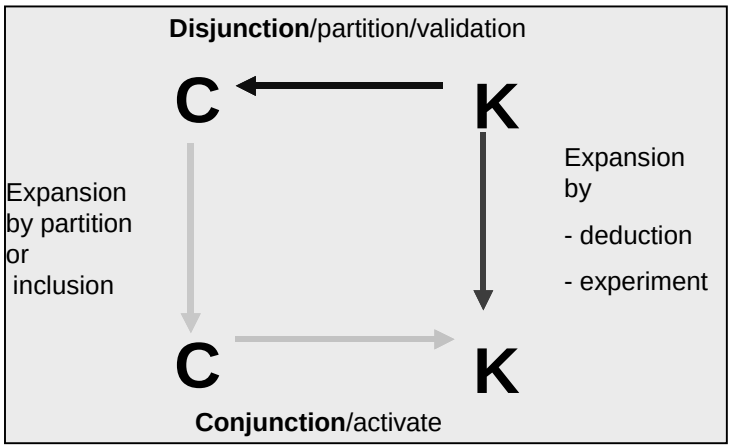


Figure 1. the design square

Another illustration of the C-K dynamics is given in Figure2. We recognize the tree structure in C, while the structure of K could be different. The analysis of the structure of K is a difficult one and it would be too long to discuss it here. We also see in this picture that any expansion in C is dependant of K and reciprocally. Any choice to expand or not in C is K-dependant. Conversely, any creation in K requires travelling by some path in C. Designs begins with a disjunction and will "end" conventionally only if some conjunction exists and is judged K-relatively as "a solution".

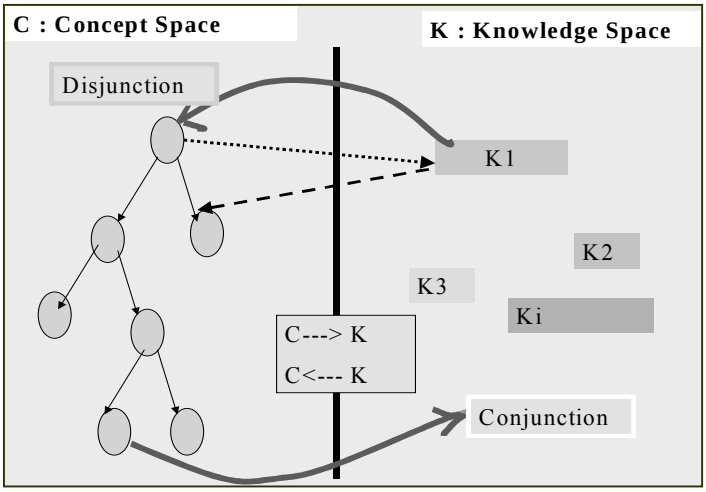


Figure 2. C-K dynamics

Considering the precise formulation of our assumptions and the dynamics of the four operators, we hope that the reader will be convinced that our approach is not a metaphor or a model of Design but a Design theory. At least, we have met our initial requisites: we have built-in creativity in the

definition of design and we have established the process by which the co-expansion of knowledge and concepts becomes possible. Moreover C-K theory offers the following results:

- It offers **a universal form of reasoning** that describes how we can think about something we partially know and expand it to some unknown definition, while not being lost in the process.
- It allows to study **the conditions bearing on any design process**: How disjunctions or conjunctions are they possible ? What is the influence of our knowledge and learning processes on design ? A rigorous examination of these questions becomes possible and will be treated in forthcoming papers. We will limit ourselves in this paper to a first discussion of the power and applications of C-K theory.

# 4. Validation and implications of C-K theory

## 4.1.How can we validate a design theory?

It seems to us that the validation of a design theory is similar to the validation of other theories like decision theory or problem solving theory. In all these cases three criteria can be used. Each of them is probably not enough, however taken together they can be more convincing. i) First criteria: the theory constitutes a good unification of previous theories about the same object. ii) Second criteria : the theory clarifies hidden properties of its object that were not visible in the previous theories and this new insight contributes to embed the theory in a more universal body of knowledge. iii)Third criteria: the theory clarifies some pragmatic issues and even offers new ways to treat them with robust expectations.

## 4.2. C-K theory as a unified theory of Design

The first advantages of C-K are its rigour and its consistency. It offers the first definition of Design that captures the singularity and disturbing nature of Design: the dual concept and knowledge expansions. It has a precise formulation that allows strong control on the propositions of the theory, provided that one accepts Set theory and modern logic as valid knowledge (always the K-relativity…). Therefore, C-K theory appears as a unified theory in the classic scientific sense: **it captures in the same framework previous theories that looked initially different.** For instance, C-K theory is both a process and a mapping. It easily models all process-based theories and clarifies their implicit hypothesis. We can use C-K to clarify the implicit conditions on K that are assumed by the German systematic to be an acceptable method. It points out clearly why Suh's axiomatic is not a design theory as there is no concept and no knowledge described by the theory. Suh axiomatic is a command and control theory helpful in some design work. C-K theory also encompasses similar attempts like Yoshikawa's general design theory or Grabowsky et al., "universal design theory". Yet, to show it in detail would need a full paper. Finally, C-K theory synthesizes the knowledge acquired in the field of design theory in a consistent way and embeds it in modern set theory.

Even, if it is impossible to pretend that there is no other way to reach the same theoretical power, in this paper we have showed that C-K theory can successfully reach the first and the second criteria. It would be too long here to discuss it capacity to fulfil criteria 3. In practice, C-K theory is now used in several companies: i) to monitor the early phases of innovative design projects ; ii) to

develop new organizational structures for innovation different from R&D organizations; iii) to memorize the results of a design works and its correlated knowledge expansions. We have discussed elsewhere how the C-K theory can be used as a useful guide for the organizing of innovation in “design oriented organisations” [3], [24], [25], [26]. However the following discussion of creativity can be seen as a first step in this direction.

## 4.2. C-K theory and creativity: a new perspective.

C-K offers also a fresh critic on usual views about creativity. The dual C-K expansion process provides direct explanation of the empirical existence of *two major types* of “inventions”.

- **Type 1 creativity: C-k expansions (large C-small k) or "conceptual innovations"**: these cases need a significant conceptual expansion i.e a large number of successive partitions in C, whereas the knowledge K used is very common to many people. Therefore, most people are extremely surprised by the result. People’s reaction to such innovative design is typically: "why didn't we think of that before!" or "gosh, that's very clever", etc. These feelings are based on the fact that all the knowledge needed was already available, yet the concept had not occurred to them. C-K theory explains why these feelings are based on an illusion: knowledge has no design value without the concepts that it helps to expand! Thus this type of ordinary and common inventions require tenacity and patience: designers must agree to **suspend the logical status of some common propositions** for a time and accept several expanding partitions before obtaining any acceptable design**.**

- **Type 2 creativity**: **c-K expansions (small C-large K) or “so called” applied Science*:*** these cases involve sophisticated knowledge with a limited conceptual development. People are not surprised by mobile phones or televisions, they are completely fascinated! Not that they had never thought of long-distance communications, but because they had no idea how to get it. Also , except for a few specialists, they recognize the concept but they are not able to explain how it works. This second type of expansion is typical of the technological world in which we live. New knowledge is produced constantly and intervenes in design processes that are completely unknown to most of us. Facing this new objects, we suddenly discover unexpected combinations of simple concepts and complex knowledge. This model of creativity had an enormous impact on our views of design: many have the illusory idea that it simply involves an "application" of scientific knowledge. Therefore, the design process becomes invisible. This view has been very influential in the education of engineers: sound knowledge in the basic sciences would be all what is needed to be a good engineering designer!

All this allows to argue about the validity of classic creativity games like “brainstorming”. If one is involved in a C-k type innovation, brainstorming will be very disappointing as the most interesting ideas (i.e. C-K disjunctions) will appear either as too daring dreams regarding existing knowledge or as too prudent ideas whose innovative power would be visible only after several expansions. Thus C-K theory tells us that there are only **two consistent creativity games**:

- adopting **daring concepts** and **quickly leaving the creativity team** and room looking outside (new data, experiment, experts...) for new knowledge expansions;
- adopting **seemingly acceptable concepts** and working hard, continuously and with patience, to expand them towards an innovative design.

## 5. Conclusion: future prospects about C-K theory

In this paper we have presented the main elements of C-K theory and showed that this theory has several advantages. It gives a rigorous definition of design and establishes the deep link existing between design and a fundamental issue in Set theory. It also unifies existing design theories and offers a precise constructive definition of the design process. More over, with C-K theory design theory has immediate connections with all others knowledge theories or forms of logic. It can claim a universal value and several promising ways are opened to further research.

- **Improving the foundations of the theory**: C-K theory has been presented in this paper with **a limited mathematical development**. Yet there is a large area of investigation in this direction. The properties of K can be studied in more detail and the structure of the four operators presents very interesting features. We can attempt to characterize the conditions that warrant the existence of disjunctions and conjunctions ; and finally investigate the mathematical and computerized tools that could capture the C-K process.

- **Improving social and management research on design**: Based on our empirical industrial observations, the value of a unified design theory that can guide innovative projects has been assessed. C-K theory fits this program in a theoretical and rigorous way. We observe a good understanding of its principles by engineers, architects or artists as it offers a common language about Design that is not dependant of the type of skill and knowledge used. It also opens a new spectrum of research in the organization of design and innovation. **Qualitative and social research on Design practice** should be revisited as new investigations are suggested by C-K theory: for instance, what is the social acceptance of concepts and disjunctions in organizations ? how are they handled ? Does team work allow for long conceptual expansions ? What is the impact of knowledge codification on the ability to design ? C-K theory offers a clear set of universal notions that can help the social researcher to analyse a design process without being biased by too restrictive visions of Design.

The variety of these new research issues is certainly a good sign of the potential of C-K theory.

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Res Eng Design (2009) 19:181–192
DOI 10.1007/s00163-008-0043-4

ORIGINAL PAPER

# C-K design theory: an advanced formulation

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Received: 20 October 2005 / Revised: 11 December 2006 / Accepted: 23 March 2008 / Published online: 19 August 2008


**Abstract** C-K theory is a unified Design theory and was first introduced in 2003 (Hatchuel and Weil 2003). The name "C-K theory" reflects the assumption that Design can be modelled as the interplay between *two interdependent spaces* with different structures and logics: the space of concepts (C) and the space of knowledge (K). Both pragmatic views of Design and existing Design theories define Design as a dynamic mapping process between required functions and selected structures. However, dynamic mapping is not sufficient to describe the *generation of new objects and new knowledge* which are distinctive features of Design. We show that C-K theory captures such generation and offers a rigorous definition of Design. This is illustrated with an example: the design of Magnesium-$CO_2$ engines for Mars explorations. Using C-K theory we also discuss Braha and Reich's topological structures for design modelling (Braha and Reich 2003). We interpret this approach as special assumptions about the stability of objects in space K. Combining C-K theory and Braha and Reich's models opens new areas for research about *knowledge structures* in Design theories. These findings confirm the analytical and interpretative power of C-K theory.

**Keywords** Design theory · Innovation · Creativity

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## 1 Introduction. C-K theory: initial reactions and issues raised

In this paper we present an advanced formulation of C-K theory, drawing on initial reactions to the theory and on new research findings. The new material helps clarify the unique properties of the theory and provides fruitful interpretations of the assumptions of other formal Design theories such as the Braha and Reich model (Braha and Reich 2003). Before outlining the issues discussed here, we begin with a brief overview of the premises of C-K theory.

### 1.1 A brief overview of C-K theory: modelling innovative design

C-K theory was introduced by Hatchuel and Weil (2003). It aims to provide a rigorous, unified formal framework for Design. It also attempts to improve our understanding of *innovative design* i.e. design which includes *innovation* and/or research as in the case of Science Based Products (Hatchuel et al. 2005). The name "C-K theory" reflects the assumption that Design can be modelled as the interplay between *two interdependent spaces* with different structures and logics: the space of concepts (C) and the space of knowledge (K). The structures of these two spaces determine the core propositions of C-K theory (Hatchuel and Weil 2003):

**The structures of C and K** Space K contains all established (true) propositions (the available knowledge). Space C contains "concepts" which are *undecidable*[1]

[1] A proposition is qualified as "undecidable" relative to the content of a space K if it is not possible to prove that this proposition is true or false in K. The notion of undecidability is well defined in number theory and in computing science (Turing's undecidability theorem).

propositions in K (neither true nor false in K) about *partially unknown* objects *x*. Concepts all take the form: "*There exists some object x, for which a group of properties* $P_1$, $P_2$, …, $P_k$ *are true in K*". Design projects aim to transform undecidable propositions into true propositions in K. Concepts define *unusual sets* of objects called C-sets, i.e. sets of partially unknown objects *whose existence is not guaranteed in* K. During the design process C and K are expanded jointly through the action of *design operators*.

**The design process and the four C-K operators** Design proceeds by a step by step partitioning of C-sets until a partitioned "C-set" becomes a "K-set" i.e. a set of objects, well defined by a true proposition in K. This process requires four types of operators: C-C, C-K, K-K and K-C. These operators are explained later in the article. The combination of these four operators is a unique feature of Design. They capture all known design properties including creative processes and explain seemingly "chaotic" evolutions of real practical design work.

### 1.2 Issues raised about C-K theory

The first publication of C-K theory attracted interest from both practitioners (Fredriksson 2003) and scholars. In recent years, C-K theory has been introduced in several industrial contexts [most of these applications have been described elsewhere (Le Masson et al. 2006)], but in this paper we focus on the reactions to the theory in academic papers. Kazakçi and Tsoukas (2005) underlined the power of the theory when compared to other theories such as Gero's evolutionary design (Gero 1996) and suggested introducing the designer's *environment, E*. This extension does not change the basic assumptions of C-K theory but suggests a practical organization of space K that helps develop new types of personal Design assistants. Salustri (2005) sees C-K theory as a "*unique and interesting Design theory*" but asked for increased rigour in its presentation. He uses C-K propositions as an inspiring source for a new language of action logic for Design. In this language, the "concepts" of C-K theory are interpreted as the designer's dynamic "beliefs" concerning design solutions. However, Salustri found no necessity to assume C-sets in his model. Le Masson and Magnusson (2002) used C-K theory to enhance users' involvement in design. They interpreted the most surprising user ideas as *concepts* which deserve further design expansion with the help of experts. Ben Mahmoud-Jouini et al. (2006) also used C-K theory in addition to classic creativity techniques to build an innovation strategy in a car supplier company. Elmquist and Segrestin (2007) modelled creative drug design with C-K theory to enrich scouting and scanning methods for the acquisition of new molecules.

As well as confirming the potential of the theory, these authors and other readers (conference and journal reviewers, workshop participants etc.) pointed out a number of issues that were not sufficiently addressed in the previous presentation of C-K theory (Hatchuel and Weil 2003): what is the definition of Design in C-K theory? How is it related to the usual pragmatic views of Design? What are the main aspects of Design that C-K theory captures better than other theories, in particular recent Design theories such as those put forward by Braha and Reich (2003)? In this paper we discuss these issues and present new clarifications and findings that we hope improve on the first presentation of C-K theory.

### 1.3 Outline of the paper

The paper is divided into three parts. In Sect. 2, we evoke the "pragmatic" definition of Design as good mapping between required functions and selected structures. Design theories generalize this definition by describing *dynamic mapping*. However, dynamic mapping is not sufficient to describe the *generation of new objects and new knowledge* which are distinctive features of Design. We show that C-K theory captures such generation and offers a rigorous definition of Design. In Sect. 3, we show how the combination of four C-K operators enables reasoning on *unknown or changing* objects. This is illustrated with the example of the design of Mg-$CO_2$ engines for Mars explorations. In this case, Design not only maps functions and structures, it also shifts the identity of the engine and the type of missions it will serve. In Sect. 4, we use C-K theory to interpret Braha and Reich's topological structures (i.e. *closure spaces*) for design (Braha and Reich 2003). We show that these models assume the stability of objects in K. Combining C-K theory and closure spaces clarifies the distinction between rule-based design and innovative design. These results confirm the explanatory and interpretative power of C-K theory. We conclude (Sect. 5) the paper by indicating some areas of research opened by these findings.

## 2 The definition of Design in C-K theory

### 2.1 Pragmatic definitions of Design

Usual definitions of Design are *pragmatic descriptions* of a professional challenge (Evbwuoman et al. 1996). Designers receive a "brief" or "specifications" of a product (or service) from a customer and in return, they are expected to offer several "proposals" or "designs" which meet these specifications. A more realistic approach to Design acknowledges a continuous interplay between designers and customers. Specifications may change in reaction to

proposals or to unexpected problems discovered during the process. In this case, Design follows cycles of mutual adjustment between specifications and solutions until a final "solution" is reached. A large amount of research into engineering design does not require a more precise definition than this. Theoretical problems only arise when design itself becomes the object of academic inquiry (Evbwuoman et al. 1996; Blessing 2003; Simon 1979). Then, simple questions unveil difficult issues: is it possible to distinguish design improvements from technological improvements? How can we establish a design methodology without a rigorous definition of Design? What are the links between Design and innovation?

#### 2.1.1 *Formal models of design: the limits of dynamic mapping*

These issues are crucial for researchers who work on design methodologies and/or mathematical representations of Design. However, even the most abstract Design theories draw on the same pragmatic definition of Design: Design is a *mapping* process between functions and design parameters or structures (Suh 1990; Yoshikawa 1981); this may be achieved in a small number of fixed steps (classic systematic design) or may follow a more evolutionary process (Gero 1996). Within the same perspective, Braha and Reich (2003) generalized Yoshikawa's Design theory and presented an encompassing model, the *Coupled Design Process* (CDP in this paper) that accounts for various properties of design including, non-linearity, non-optimality, conflicting goals and exploratory processes. In their approach, Design is modelled as a *dynamic mapping process* between a function space F (set of functions) and a structural space D (set of design options or parameters). A special form of this co-evolution is modelled with *closure spaces* which are an interesting way of describing *refinement steps for functions and structures (*In part 3, we discuss the interpretation of closure spaces with C-K theory).

However, is the pragmatic definition of Design a rigorous approach to design processes? And consequently, is dynamic mapping *sufficient to model* Design? The answer is negative, as we can find situations which require no design activity, but where dynamic mapping is nonetheless necessary. Moreover, dynamic mapping does not capture the main operations involved in design situations where new objects have to be generated.

#### 2.1.2 *Dynamic mapping in problem-solving: the example of a lost driver*

Let us take the example of a driver lost in an unknown country. He is looking for a "*convenient hotel, not too far away and not too expensive*". The driver has no guidebook to the country and has to ask the people he meets for information to help him adjust his own desires to the solutions available. Herbert Simon (1979) often used similar situations to describe problem-solving procedures based on the dynamic fit between solutions and satisfaction criteria. However, the driver will not *design* the hotel where he decides to stay. We could say that he designs a *decision function* to find it; and Decision theory can be seen as a minimal form of design. Yet, Design usually involves far more than selecting existing solutions. Therefore, dynamic mapping is not a distinctive aspect of Design, and we need to identify the features of design that it fails to capture.

### 2.2 Design as the generation of new objects

Let us introduce example A, inspired by a real case study. We will use it in the following sections of the paper to illustrate the propositions of C-K theory.

**Example A: designing an Mg-$CO_2$ engine for Mars exploration** Future Mars missions face a well known energy problem. Spaceships have to transport all the propellant for the Mars exploration and the return journey; in view of the great distances involved, this is no minor issue. Given that Mars' atmosphere is made of $CO_2$, this could be a good oxidant for burning metals such as magnesium. Could it be possible to "refuel" with $CO_2$ on Mars? Scientists suggested the option of designing Mg-$CO_2$ engines for Mars missions.[2]

Example A introduces a common, yet distinctive, feature of Design. The lost driver had neither to *design* hotels nor *to make them exist*. He had to *find* and *choose* them. Mathematically, the driver problem can be approached by programming heuristics, problem-solving theory and multicriteria decision-making (Simon 1969). These models fully capture the dynamic mapping between solutions and criteria, but not the "*generation*" of new things, i.e. in example A, *the definition* of a new engine whose principles are not necessarily known today, as well as the identification of conditions guaranteeing *the existence* of such an engine. Hence, a complete definition of Design has to account for *two joint processes* that are not clearly outlined by the pragmatic definition:

- dynamic mapping between specifications and design solutions.
- The generation of objects unknown at the beginning of the process and whose existence could be guaranteed

[2] This case was developed using C-K theory by our student Michael Salomon during his Major course for the engineering degree at *Ecole des Mines de Paris* in collaboration with CNRS-LCSR. His work contributed to the material published in Shafirovich et al. (2003).

by knowledge that may be discovered during the process.

The combination of these two issues leads precisely to the premises of C-K theory.

## 2.3 The premises of C-K theory: meaning and role of "Concepts"

### *2.3.1 The logic of Design "briefs"*

The starting point of a design project is described in pragmatic terms as a "brief", an "idea" or "abstract specifications". These expressions attempt to describe an object that is not completely defined and whose conditions of existence are not completely known. Therefore, the only way to start the design process is to formulate an *incomplete, even ambiguous group of desired properties* for this object. To capture the reasons and rationale for such odd formulations we need to model both what is known and what is partly unknown. The two spaces of C-K theory fulfil this need.

**Definition of space K** We assume an expandable Knowledge space K, which contains true *propositions* characterizing partly known *objects* as well as partly known *relations* between these objects. In K, all propositions are true or false. K is *expandable* i.e. the content of K will change over time and definitions of some objects of K may also change. In practice, K is the established knowledge *available* to a designer (or a design team). Conflicting views and uncertainties are also true propositions of K. In example A, K contains several knowledge bases: Mars science, combustion science, future Mars missions, Mars exploration politics and main actors.

**Definition of space C and "Concepts"** We consider propositions of the following type P: "*There exists some entity x (or a group of entities) for which series of attributes* $A_1$, $A_2$, $A_k$ *are all true in K*". We define P as a *concept* relative to K if P is *neither true nor false* in K. We assume that Space C is expandable and contains all the concepts relative to K. Space C is a key premise in C-K theory. Its unusual structure controls the main properties of C-K theory and captures the core features of Design. It unravels the nature of briefs and allows new objects to be generated during the design process.

### *2.3.2 Why Design begins with a concept?*

Concepts clearly capture the nature of briefs: either the brief is "undecidable" in K or the design process has already been completed. Concepts also confirm that ambiguity, ill-defined issues and poor project wording are not problems or weaknesses in design, they are necessary! Moreover, undecidability and incomplete concepts can be seen as consistent *triggers* once design is perceived as an *expansion* process (see below). For the same reasons, concepts are not propositions that can be tested like *scientific hypotheses*. As the latter have to be assumed as true this would mean that the design work has already been done. For instance, in example A, we cannot begin to design a new Mg-$CO_2$ engine for Mars exploration and immediately test it, but we can check whether *a design proposal is acceptable as a concept*.

Coming back to our Mg-$CO_2$ engine, let us consider the proposition $C_0$: "*There is an Mg-$CO_2$ engine that is more suitable to Mars missions than classic engines*". We then have to prove that it is a concept. Obviously, it was not possible to prove that $C_0$ was true with existing K, but was $C_0$ false in K? In fact, it needed only one proposition in K to "*kill the concept*". To meet the requirement of a good propellant, the combustion of Mg and $CO_2$ had to create sufficient "specific impulse" (i.e. energy for movement), otherwise there would be no engine at all. This property could be tested *without fully designing an engine* and was therefore assessed scientifically. This test simply proved that there was no proposition within existing K that proved that $C_0$ was true or false. Thus, $C_0$ was a suitable concept for further design. According to Pahl and Beitz's systematic design (1984) the main function of an engine is to produce sufficient energy; we therefore simply checked this function. Yet, Pahl and Beitz recommend modelling *all* the main functions in a first design phase, a task which was clearly impossible in this case. Moreover, the satisfactory level of specific impulse from a propellant's combustion can be interpreted as a function, as a conceptual model or even as an embodiment solution. This illustrates the ambiguity of classic design phases when design is innovative. C-K theory frees the designer from such predefined steps and categories. What counts is the consistency of the operations between C and K and the expansion produced in the process.

### *2.3.3 Design simultaneously expands C and K*

The pragmatic view of design describes a dynamic mapping process between specifications and solutions. However, it is clear that this approach fails to account for the expansions occurring in space C and in space K during the actual process. Let us start a design process with a concept C: "*there exists an x with a set of attributes* $A_0$". At step i, the designer has changed the initial set of attributes $A_0$ into $A_i$ by adding or subtracting new attributes and has introduced some partial design parameters $D_i$. At this stage, a new proposition $C_i$ has been formed: "*There exists x with a set of attributes* $A_i$, *which can be made with a set of*

*design parameters* $D_i$". There are three possibilities for the logical status of $C_i$ in K:

1. $C_i$ is false in K and the design process has to change some of the $A_i$s or the $D_i$s;
2. $C_i$ is true in K and ($D_i$, $A_i$) is one candidate as a "solution" for $X$; we call it a "*conjunction for x*";
3. $C_i$ is neither true nor false in K: hence it is *a new concept* and we have to continue the design process.

In the two-first cases *we have added new propositions to K*; in the third, we have added a *new concept* to C. Thus design not only generates "solutions" but also, by the same procedures, *new concepts* and *new propositions in* K. It is therefore more rigorous to describe the design process as a *dual expansion* of spaces C and K. This finding can also be based on empirical observations. Design often generates knowledge that is finally used for a different purpose than the initial brief; or stops at *an intermediary concept* which can even be sold as such. For example, the designer of a movie may stop after writing the story and sell it to a film maker who will adapt it to suit his or her own views. Hence, the premises of C-K theory are both more rigorous and more realistic than the pragmatic definition of design.

### 2.4 Conclusion of Sect. 2: a definition of Design

All the premises and initial propositions of C-K theory are essential in formulating a highly precise, general definition of Design.

**Definition** Design is a reasoning activity which starts with a concept (an undecidable proposition regarding existing knowledge) about a partially unknown object x and attempts to expand it into other concepts and/or new knowledge. Among the knowledge generated by this expansion, certain new propositions can be selected as new definitions (designs) of $x$ and/or of new objects.

This definition does not contradict pragmatic definitions of Design. It is more general and more complete. It introduces the generation of new objects and consistently defines the departure point for a design project. In the next section, we illustrate this definition *in action*, as all operations modelled by C-K theory can be deduced from these premises.

## 3 C-sets and C-K operators: expanding knowledge and revising object identities

Pragmatic accounts of Design portray the changing, often surprising paths followed by designers groping about a solution. C-K theory captures this process and explains its specific rationality and logic by analysing the simultaneous expansion of C and K. However, space C and space K follow two different, albeit interdependent, expansion patterns. We begin by examining the specific role of space C as it supports the logic of the whole process.

### 3.1 A central property of C-K theory: revising the identities of objects in Space C

**Identity of an object in K** Let us assume, in space K, propositions about a collection of objects O which *all* possess an attribute $A_0$ (example: "all known car tyres are made of rubber"). Thus, $A_0$ ("made of rubber") can be considered as a partial element of *the identity* of O. Let us put forward the proposition Q: "*There exists O without* $A_0$" ("there exist car tyres without rubber")". If K contains a *universal proposition* which says that all O, whatever the time or place, have the attribute $A_0$, then Q is false. But if K only contains the proposition: "*All known Os have the attribute* $A_0$"[3] then Q is a potential concept that may lead to a *revision of the identity* of O. As C allows for such potential changes in the identities of objects in K, C-K theory therefore captures *the birth of new objects*.

This property of Space C was not emphasized sufficiently in the first presentation of C-K theory (Hatchuel and Weil 2003). It highlights the key importance of space C and clarifies the power of design reasoning. This property that we call "*power of expansion*" is, to the best of our knowledge, a unique way of capturing creativity or invention *within* Design theory and not as an *external addition*. However, this power of expansion depends on particular conditions in K Whenever possible, *universal propositions* should be avoided in K as they are logical obstacles to the revision of object identities. Thus C-K theory supports the intuitive notion that Design is not very consistent with universal, fixed object identities. The formulation of undecidable propositions concerning partially unknown objects obviously requires some precautions and we therefore introduce the notion of *concept-sets*, or C-sets, which are a powerful analytical tool.

### 3.2 Concept-sets as sets of partially unknown objects

In space C, we define *concept-set* as follows: a set defined by a proposition which is a concept relative to K. For example, if C is the concept "*there exists an x with A(x)*", the C-set is the set of all objects x that verify A. C-sets present surprising properties. They are *neither empty nor non-empty*. This result is a corollary of the definition of a

[3] For example usual major premises in syllogism as "all humans are mortal".

concept. To prove that C-sets are non-empty, the only way is to exhibit an *x* verifying A in K. But this would mean that C is true in K, hence C is not a concept. The same type of proof can be used for the "empty" case. What is the meaning and role of C-sets? In classic programming theory or problem-solving theory (Simon 1969; Simon 1979; Simon 1995), the task is to explore a *problem space* containing a list of potential or approximate solutions. All solutions may not be accessible; it is however assumed that solutions are built by the combination of well defined objects like, for example, in the game of chess. In contrast, Design faces situations where *it is not possible to define even an infinite list of known design candidates or even to define what such candidates are*. C-sets capture this situation by modelling collections of *partially unknown objects* which verify a proposition which is *undecidable in K*. In example A, the set of "all Mg-$CO_2$ engines for Mars explorations" is clearly a C-set. It is not only impossible to list all possible Mg-$CO_2$ engines, but the design parameters of such engines are also partially unknown when design begins. C-sets are special sets which, to our knowledge, have not been described in the Design literature to date. To rigorously define C-sets, we make some restrictions to the standard axioms of set theory.

**Axioms for defining and partitioning C-sets** C-sets are defined within a restricted axiomatic of Set theory. Namely ZF (Zermelo–Fraenkel) without two important axioms: the axiom of choice (AC) and the axiom of regularity (AR) also known as axiom of foundation (every non-empty set A contains an element B which is disjoint from A).[4] This axiomatic of Set Theory is described as ZF-non AC, -non AR. Axiom of choice and axiom of regularity are respectively the warrantors of the existence and selection of one element in a set (Jech 2002). As C-sets are neither empty nor non-empty, they cannot verify these axioms. These axioms are usually formulated on the condition that the set is non-empty, a condition that we can neither accept nor reject for C-sets (Jech 2002). Although some authors (Salustri 2005) do not see the need for the axiomatic of C-sets, we stand that it captures the neglected, yet crucial, fact that during the design process we manipulate collections of *objects* which do not have *operational and stable* definitions. Designers work with sketches, models or mock-ups which are actual *representations* of a family (often infinite) of future objects which are still partly unknown and related to undecidable propositions. They cannot logically extract and manipulate a single, well defined design solution *until it has been decided conventionally that design has ended.* These families of representations have the properties of C-sets.

The axiomatic of C-sets explains the structure of expansion of space C. As shown in Hatchuel and Weil (2003), due to the rejection of the axiom of choice and axiom of regularity, the *only* operations allowed on C-sets are *non-elementary partitions (or inclusions)*. These partitions are core operations of C-K theory. Design can only partition an initial concept in the hope that this expansion of attributes will create useful new concepts and new knowledge. The partitioning attributes in C must be extracted from K. In return, K is expanded by attempts to check the logical status of propositions. Four operators (C→C, C→K, K→K, K→C) produce these expansions which transform C into K and conversely. This C-K interplay is illustrated below with a summary of the Mg-$CO_2$ case. We underline how C-K operators organize the design process and also allow for a *flexible, changing definition of objects.*

### 3.3 The operators of C-K theory: an illustration with example A

Having assessed that "*there exists an Mg-$CO_2$ engine for Mars exploration…*" was a concept (see Fig. 1), the next stage is to partition this concept in space C.

#### *3.3.1 Phase 1: partitioning with known Mars missions*

What was known about Mg-$CO_2$ engines in K? That they should perform better than classic ones. And about Mars missions? The available options where found (C→K) in the previous Mars missions simulation and the validation tools of the Space Agency concerned. Partitioning with each mission scenario (K→C) generated Mg-$CO_2$ concepts that could be compared to other propellants *without further descriptions of the engine* (K→K). However, it was found

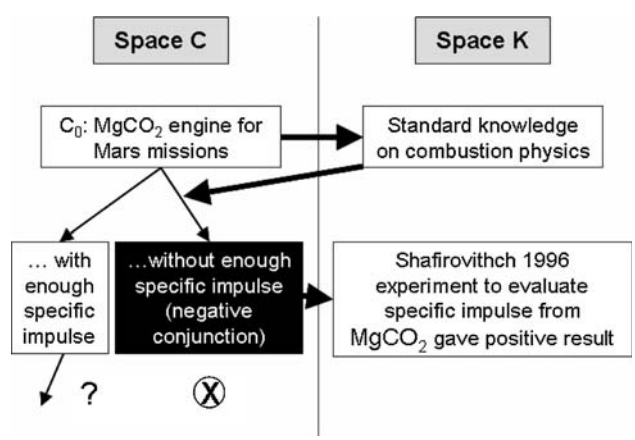


**Fig. 1** Assesing a Concept of Mg-$CO_2$ engine

[4] The rejection of the axiom of foundation was not mentioned in Hatchuel and Weil (2003). It was suggested to us by our student Mathieu le Bellac in his minor dissertation for the Master in management (MODO) at Université Dauphine.

that if usual mission criteria were maintained, no Mg-$CO_2$ engine would globally perform better than standard propellants! In other words, for all known mission scenarios added to $C_0$, the new proposition was false in K. To carry on the design process new partitions of $C_0$ were needed (i.e. partitioning the box "other?" in Fig. 2). Meanwhile, what happened in K? The scenario analysis had created new and unexpected knowledge. It appeared (K→K) that each time Mg-$CO_2$ engines were used *only on Mars* the mission performed better than others with classic criteria. This new proposition in K (see Fig. 2, the black block with white letters in K) offered a new "expanding" partition (see below).

### 3.3.2 Phase 2: revising the identity of the engine

This new proposition suggested (K→C) a new concept: "*there exists an Mg-$CO_2$ engine used only on Mars during Mars explorations*" (see Fig. 3). Once again, how could we partition this new concept? Could we expand the knowledge available on the missions performed on Mars (C→K)? The question stimulated additional research (K→K) which showed that existing mission scenarios poorly modelled activities that could be performed on Mars. *The rover solution was too implicit in existing definitions of missions to perform on Mars*. Instead, a new typology of missions was established with new models of *mobility,* new *scientific experiments*, new *communication tasks, etc.* This new knowledge on Mars exploration generated new partitions for C. For example, rapid refuelling of $CO_2$ for unplanned moves (see Fig. 3) in case of environmental dangers (dramatic storms are common on Mars) was a new potential attribute of the engine. At that stage, with a new concept such as *"an Mg-$CO_2$ engine, only used on Mars for a new type of mobility that could be either planned or unplanned*", the identity of the designed object *was shifting*. The first concept was evaluated as a complete

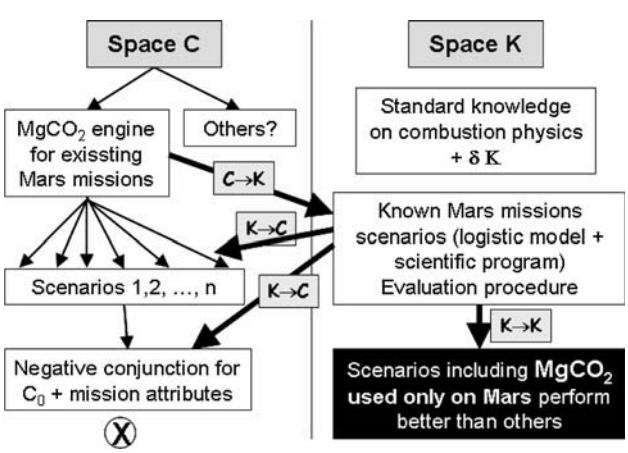


**Fig. 3** Revisiting the identity of the engine

alternative to existing propellants. The new concept of "an Mg-$CO_2$ engine" was now associated with a wide variety of movements on Mars which evoked a *new type of vehicle* for Mars exploration: a "hopper" (see Fig. 4) (Shafirovitch et al. 2003). It is worth mentioning here that this *identity shift* is captured by a group of partitions that could not be activated at the beginning of the process.

### 3.3.3 Phase 3: designing for prototyping

Thus, a new concept for the engine led to the definition of a new concept of vehicle, and large amounts of new knowledge about Missions on Mars were then generated. What was the next step (C→K)? The standard knowledge was that "An Mg-$CO_2$ engine for a Mars hopper" should be testable by earth prototyping". But which prototype should be designed? Answering this question meant searching (K→K) for testable conditions (K→C) that would partition the concept of an Mg-$CO_2$ engine for a Mars hopper. These conditions were obtained by a computation tool (K→K) that defined mass limits for the engine and its associated $CO_2$ plant. This introduced a new




**Fig. 2** Attributing known missions

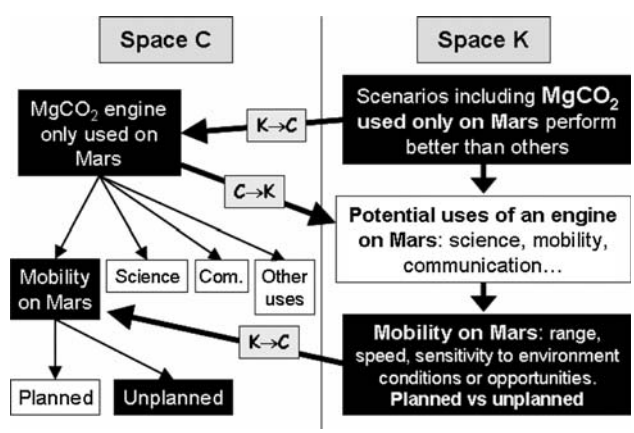


**Fig. 4** Designing for prototyping

proposition in K: "*an Mg-$CO_2$ engine for a Mars hopper that enables extended mobility and unplanned movements has an engine mass and a $CO_2$ plant mass limited to a defined domain*". This clarified the conditions for the design of a new prototype: such demonstrator should help to check whether the design domain in question was a killer criterion for the engine concept. The following partitions were all oriented towards the design parameters of the prototype.

Example A has been described in more detail in Hatchuel et al. (2004). It has also been modelled by Salustri (2005). The above overview illustrates an important property of C-K theory: a small number of operators capture *the generation and changing identity of an object*, a complex process which would seem "chaotic" if C and K were not modelled simultaneously and interdependently.

## 3.4 A summary of C-K operators

We shall now summarize the specific functions of the four operators illustrated in example A.

### *3.4.1 The four C-K operators*

- C→K operators search *attributes* in K which can be used to partition concepts in C.[5] They also contribute to the *generation of new propositions in K*. Each time a concept $C_0$ is modified by a new attribute we must check whether the new proposition is still a concept. This does not simply involve answering 'yes' or 'no'. New propositions are generated that may be new sources of attributes for the following partition (this is what happened for the Mg-$CO_2$ engine mission tests). Thus concepts have *an exploratory power* in K through their own validation.
- K→C operators have symmetrical functions to the previous ones. They generate tentative concepts by assigning new attributes. They also assess the logical status of new concepts and maintain the consistency of the expansion of C.
- C→C has been seen as a *virtual* operator (Kazakçi and Tsoukias 2005) as the main operations travel through K. In fact, it is of utmost importance in the formation of the results of a C-K process. "Design solutions" are *chains of attributes that contains $C_0$ and form new truths in K*. Hence, C→C operators are graph operators in Space C that enable the analysis of chains, paths, sub-graphs, and so on.
- K→K operators encompass all classic types of reasoning (classification, deduction, abduction, inference, etc.). Moreover, any design methodology that can be performed as a program (or an algorithm) without any use of concepts and C-sets is finally reduced to a K→K operator (for example, the genetic algorithm for optimizing an engineering system uses only standard calculus and logics).

The structure of these operators once again underlines *the major role of space C*. It gives birth to *three new operators* which do not belong to classic modes of reasoning. This is a new confirmation of the *specificity* of Design compared to other modes of reasoning which can be described using only K→K operators.

### *3.4.2 The asymmetric structures of spaces C and K*

These operators generate two different yet interdependent structures in Space C and Space K. In C we can only partition C-sets as no other operations are allowed. Hence, C is always *tree-structured* and presents a divergent combinatorial expansion, whereas K is expanded by new propositions that have no reason to follow a stable order or to be connected directly. As suggested by Fig. 5, K grows like an *archipelago* by the adjunction of new objects (new islands) or by new properties linking these objects (changing the form of the islands). The complete mathematical treatment of these properties is not straightforward. It is beyond the scope of this paper and will be treated in forthcoming papers.

## 3.5 Synthesis: expanding partitions and the changing identity of objects

C-K operators simultaneously model dynamic mapping and the distinctive feature of Design: *the generation of new objects*. This is achieved by the specific logic of C and the interplay between C and K. If we are limited to K-K

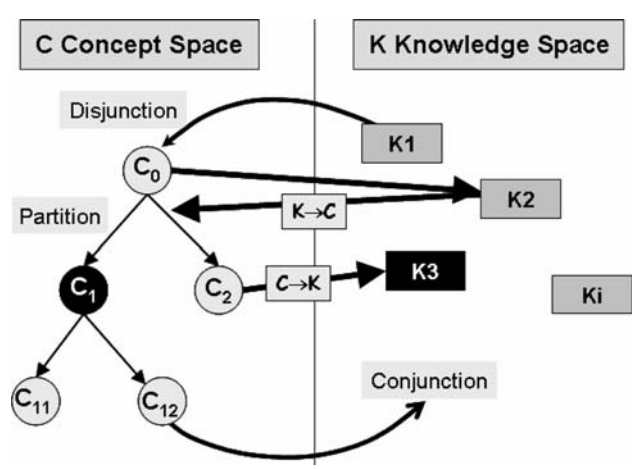


**Fig. 5** Asymmetric structure of spaces C and K

[5] It should be noted that subtracting an attribute is equivalent to adding the negation of this attribute.

operators, we can prove theorems and simulate dynamic mappings, but the definition and identity of known objects remain stable as long as no paradox or contradiction appears. Thanks to Space C, we capture a more flexible logic. Given any object O, we can generate a concept Co if we are able to formulate an *undecidable* proposition in K. The key mechanism of this undecidability is the addition of an attribute to $C_0$ which is *not part of the existing knowledge* about O in K. For instance, "There exists a wireless home TV" would be a potential concept if "wireless" was neither a known attribute of existing home TVs, nor an attribute forbidden by existing knowledge. This would be an *expanding partition of Home TVs*. However, the same attribute ("wireless") is a "*restricting partition*" for phones, as mobile phones are well known to us. Expanding partitions are possible only in C, where they help to formulate concepts. They are the instruments which generate new objects, and C-K interplay is the source that provides new potential expanding partitions. More profoundly, expanding partitions reveal the *incompleteness* of K about O or the degree of "unknownness" of O in K. They are also powerful analytical tools for the study of other Design theories.

## 4 The interpretative power of C-K theory: a discussion of Braha and Reich's topological structures for Design

In this section we underline the interpretative power of C-K theory by analyzing a Design model proposed by Braha and Reich (2003), the *Coupled Design Process* (CDP).[6] According to the authors, CDP is more general than Yoshikawa's General Design Theory (Yoshikawa 1981; Reich 1995). We do not discuss this issue here, but simply establish that interpreting CDP with C-K theory highlights the meaning of the topological assumptions of CDP and opens new paths for further research.

### 4.1 Overview of CDP: modelling with Closure Spaces

CDP maintains the pragmatic distinction between a space of functions $F$ and a space of structures (or design solutions) $D$; $F \times D$ is called the *Design Space* and an element $<f, d>$ of the design space is called a *design description*. The designer is assumed "*to start with an initial description* $<f_0, d_0>$". He then transforms this description through a sequence of $<f_i, d_i>$s; each transition is interpreted as "a *simultaneous refinement*" of the structural and functional solutions. Moreover, to cast these transitions more formally, the authors suggest a specific topological structure for $F$ and $D$ based on *closure spaces*. It is assumed that in $F$ (or in $D$) there is a list of functions which presents a specific *order structure:* between two functions $f_i, f_j$ there is an *order relation*: $f_i$ "*is generated by*" $f_j$, which means that $f_j$ *refines* $f_i$. The closure of a function $f_0$ is the list of functions that "generates" $f_0$ (or "refines" $f_0$).

All these structures allow the authors to define a finite sequence of refinements of either functions or structures which generate a possible dynamic mapping process for the designer: "*the designer starts with a candidate design solution* do *that needs to be analyzed, since its structural description is not provided in a form suitable for analysis. To overcome this problem the designer creates a series of successive design descriptions such that each design description in this "implication chain" is implied by the design description that precedes it*" (Braha and Reich 2003) (p.191). Design stops when the mapping is successful or when no refinement is possible and "*this situation can trigger the knowledge process in an attempt to continue the refinement process*."

CDP and C-K theory have many similarities. They both describe a dynamic refinement process. However, interpreting CDP with C-K theory highlights the implicit assumptions of CDP on three important issues: the departure point of a design process, the meaning of closure spaces and the "refinement" model.

### 4.2 The initial proposition of a design process

The departure point of CDP is defined with vague formulations. The authors describe $<f_0, d_0>$ as an "*abstract formulation*, a "*first idea of a solution from the designer*" that is still incomplete and ill-defined. Yet, they do not discuss the status of $<f_0, d_0>$ in relation to existing closure spaces of $F$ and $D$s. Two additional assumptions are necessary to clarify the status of $<f_0, d_0>$:

1. $<f_0, d_0>$ is not contradictory to what is known about the closure of $F \times D$;
2. $<f_0, d_0>$ is not a direct deduction of a subset of the closure of $F \times D$, otherwise the design work has already been done.

Without such assumptions CDP cannot easily assess whether $<f_0, d_0>$ is really a design problem. From the point of view of C-K theory, the first step would be to check whether $<f_0, d_0>$ is a *concept* within *existing* knowledge and to prove the undecidability of $<f_0, d_0>$ in K. This leads to the reverse question: what are the topological structures of $F \times D$ that make a proposition such as $<f_0, d_0>$ undecidable i.e. *neither implied by* these structures, nor forbidden (made false) by them? This remark is typical of how C-K theory can stimulate new research in the direction opened up by Braha and Reich.

[6] The acronym CDP is not mentioned by the authors, but is used here for the sake of concision.

### 4.3 The topological models of functions and structures: rule-based design and stable object identities

CDP models a refinement process of functions or structures with topological structures describing order relations. These assumptions can be interpreted as specific, stable properties of certain objects. In the language of Computer Science or Artificial Intelligence, closure spaces capture knowledge structures, generally referred to as "object models" (Abadi and Cardelli 1996). Our interpretation is confirmed by the car design example used by the authors. They describe the car as an object for which the available knowledge is modelled by standard production rules (if A then B). Design reasoning is thus equivalent to an expert system using forward and backward rule activation. More generally, assuming stable closure spaces can be interpreted as assuming stable object identities. To say that $f_i$ *is generated by* $f_j$ (or $f_j$ *refines* $f_i$) is equivalent to saying that there exists an object "O" such that *if* $f_j$ *is true for O then* $f_i$ *is true for O*. The authors clearly acknowledge this interpretation as they establish a clear equivalence between rule-based design and stable closure spaces. Therefore, according to the topological assumptions of CDP, Design is a program which aims to combine existing objects that can be described in varying detail. The task of the designer is therefore to look for successful mappings, using increasing levels of refinement. However, no new objects can be generated if the refinement is always controlled by *pre-established closure spaces*.

This limitation disappears with C-K theory. Functional and structural closure spaces are considered as transient propositions in K, while partitions in C attempt to reshape *closure spaces* in K. Braha and Reich's topological structures can even be used as *an interesting design test:* the degree of revision of *F* or *D* closure spaces can be seen as an indication of the degree and extension of innovativeness of a design. In the case of the Mg-$CO_2$ engine, the function "mobility on Mars" was initially modelled by a closure function space that *was restricted to standard known* missions implicitly linked to the "rover" solution, a closure in the design parameters space. This confirms the need to study not only the *F* and *D* closures but also the $F \times D$ topological structure, at least to avoid *an implicit dependency between functions and structures that could be hidden by the separate closures*. C-K theory avoids this classic design trap by allowing for the revision of existing closure spaces.

### 4.4 Closure spaces and expanding partitions

Braha and Reich mention the important trap of "*poor quality knowledge*" that can lead to *"potentially exploring only inferior parts of the closure, leaving out the more promising solutions*". Yet, without explicit modelling of a space of knowledge, this type of judgement on the available knowledge is not modelled in the theory. Instead, if we assume that closure spaces are always K-dependent, *innovative design* can be approached by the following issue: how can we revise an initial closure space during the design process? Within C-K theory the answer is straightforward: the regeneration of closure spaces can *be directly linked to expanding partitions*. These partitions do not *refine* a function or a structure, otherwise they would be *restricting* partitions. Instead, the former partitions expand a concept and/or generate new knowledge that can change the boundaries and content of closure spaces. Describing the refinement process of a functional space, Braha and Reich remark that it can lead to a special list of functions that *does not belong* to the closure space : "*specification lists that are not included in F and such that each one generates specification lists in F*". In our view, this remark precisely describes a meta-structure connecting closure spaces in K. The authors associate such meta-structures with collaborative design[7] where designers share their colleagues' knowledge. However, more generally speaking, we can view any knowledge space K as a composition of *partly connected multiple transient closure spaces*. The task of expanding partitions is precisely to generate new connections which will prepare for the progressive *reshaping* of the closure spaces. This is exactly what is captured by C-K theory. In return, the closure space model confirms that expanding partitions are not "refinements". It also helps to understand that the dual expansion of C and K changes the definition of objects by allowing the reshaping of implicit closure spaces that may act as initial patterns in K.

Finally, this new perspective on the topological structures proposed by Braha and Reich (2003) does not refute the value of these structures in terms of modelling. On one hand, the notions of C-K theory (mainly concepts and expanding partitions) clarify the assumptions behind these topological structures. On the other hand, such topological structures can be seen as *interesting yet specific models* of the content of space K. Closure spaces can capture GDT, rule-based design and machine learning heuristics. Thus, by combining the two theories, we can establish highly general and powerful propositions:

**Proposition 1** When space K is only defined by stable, separate, closure spaces, then C-K theory and CDP describe similar processes, and Design can be modelled by Knowledge-based and learning algorithms.

[7] We can also recognize a meta-structure in the logic for "infused design" proposed by Shai and Reich (2004a, b), a model for the aggregation of several knowledge bases in order to support collaborative design.

**Proposition 2** If space K is described by transient closure spaces and by meta-structures linking these closure spaces, then C-K theory predicts that innovative design solutions (conjunctions in K) are always linked to a regeneration in the closure spaces.

## 5 Conclusion

In this paper we have made several steps towards an advanced formulation and the validation of the specific properties of C-K theory. The main results are as follows:

*Design is not only a dynamic mapping process between functions and solutions*. Design theory also has to describe the generation of new objects. Crucial elements of C-K theory capture this logic. The undecidability of concepts operationalizes the specific nature of design situations and explains the rationality of "briefs". Therefore, Design cannot be simply described as a problem-solving procedure. It is captured far better by the dual expansion of two different cognitive regimes: the *flexible approach* of C and the *truth-oriented logic* of K. As C-K theory accounts for this specific logic of Design, it provides a formal definition of Design which makes up for the shortcomings of pragmatic definitions of Design.

*If Design is both a dynamic mapping process and a generation process for new objects, it requires four C-K operators as models of thought*. Design theory extends known models of thought by introducing new analytical tools such as concept-sets based on "K-undecidable" propositions. Without such tools, Design theory is simply reduced to standard models of thought (K-K operators). By introducing these reasoning instruments, we have by no means fully modelled imagination, creativity or even serendipity. But at least C-K theory offers a framework that rigorously includes a key feature of innovative design: namely, the revision of the identity of objects and the possibility of expanding partitions.

*The high generality and the modelling capacity of C-K theory are powerful instruments for the interpretation of other Design theories*. Our discussion of Braha and Reich's topological structures is an example of this interpretative power. C-K theory helps to identify closure spaces of F and D as assumptions about the stability of objects in space K. This stability is consistent with rule-based design. Simultaneously, the strong propositions made by Braha and Reich can be used in combination with C-K theory to offer new propositions at a level of generality that is seldom reached in Design. This confrontation should be fruitful for both theories.

A variety of research issues can now be examined as a result of this progress in the consolidation of C-K theory.

*C-K theory and topological structures of knowledge*: the discussion of Braha and Reich's work calls for a systematic characterization of different types of structures in Space K and the corresponding Design theories that these structures allow. For instance, if closure spaces support rule-based design, which structures of K are consistent with systematic design *or different degrees of innovation* in the revision of objects? As we mentioned earlier, we must avoid universal propositions that rigidify the identities of objects. In this perspective, Doumas (2004) suggested exploring the type of design that would be predicted by C-K theory with a model of Knowledge built on "fluid ontologies" as proposed by Hofstader (1995). Such ontologies could be interpreted as fuzzy definitions of objects or even fuzzy closure spaces; however, additional research is required to establish this sort of equivalence.

*C-K theory and research on creativity*: In the past decades, engineering design literature has mainly borrowed results from the literature on creativity. There is now a fresh, stimulating opportunity: to explore how C-K theory could contribute to the field of Creativity. Ben Mahmoud-Jouini et al. (2006) and Elmquist and Segrestin (2007) used C-K theory to model creative processes in industrial R&D contexts. Such encouraging empirical results will be consolidated at a more theoretical level.

These research issues will be addressed in the future. In forthcoming papers we shall also back up these findings with a more complete presentation of the mathematical foundations of C-K theory.

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# Design Theory

## Methods and Organization for Innovation

Springer

# Chapter 4
# Designing in an Innovative Design Regime—Introduction to C-K Design Theory

Innovation in the 20th century was not just a singular event, but was continuous, incremental, robust—powerful. It was intentional, organized, manageable and controllable. The aim of innovation in the 21st century is to maintain the same constancy and the same power, while at the same time being radical, disruptive and creative. Stable dominant designs built the generative bureaucracies of the 20th century; in the 21st century, new design organizations are aiming to sweep aside, break and continuously regenerate the rules. The second industrial revolution invented the rule-based design regime, and by the same token it was this very regime that made this revolution possible. Following this logic, innovative design might be the heart of the revolution to come. What theories these days allow us to consider a continuous disruption? What methods and organizations today allow the implementation of these new innovative design regimes? The last few decades have seen the invention, construction and spread of theoretical frameworks and new practices. These will be studied in the next two chapters. Just as for rule-based design, we shall begin by studying the logical processes of innovative projects under innovative design (in this Chapter) before turning our attention to infrastructures and ecosystems in Chap. 5.

## 4.1 Reasoning in Innovative Design—C-K Theory

Design theories have enjoyed a revival over the last twenty years, centered about the theoretical schools in Japan (Tomiyama and Yoshikawa 1986; Yoshikawa 1981), America (axiomatic design (Suh 1990, 2001)—as seen in the previous chapter), Israel (Coupled Design process (Braha and Reich 2003) and Infused Design, (Shai and Reich 2004a, b)) and France especially. C-K theory appears not only as one of the most promising formalisms but also the most mature and, formally, one of the most generic and generative (see Hatchuel et al. 2011a and later



P. Le Masson et al., *Design Theory*,
DOI 10.1007/978-3-319-50277-9_4

in this chapter). We shall therefore build an approach to innovative design regimes based on this formalism, and will then examine the relationship between C-K theory and other formal design theories.

### *4.1.1 Origins and Expectations of C-K Theory*

C-K theory was introduced by Armand Hatchuel and Benoit Weil (Hatchuel and Weil 2003; Hatchuel and Weil 2009) and is today the subject of numerous articles in the literature (e.g. For a summary over 10 years of C-K theory, see (Benguigui 2012; Agogué and Kazakçi 2014); For practical applications in various contexts see (Elmquist and Segrestin 2007; Ben Mahmoud-Jouini et al. 2006; Hatchuel et al. 2004, 2006; Gillier et al. 2010; Elmquist and Le Masson 2009) recent work covers both its implications and its new developments, for example: (Kazakçi and Tsoukias 2005; Salustri 2005; Reich et al. 2010; Shai et al. 2009; Dym et al. 2005; Hendriks and Kazakçi 2010; Sharif Ullah et al. 2011)). In this chapter we make use of the most recent formulations (Hatchuel et al. 2013) but we provide the fundamental principles without necessarily giving the details of the formalisms.

The expectations of C-K theory are fourfold:

1. A "unified" Theory
2. A formalism for "Radical Creativity"
3. A method to extend the lists of DPs and FRs
4. A theory and method to overcome fixation

#### 4.1.1.1 Expectations from the Point of View of the Professions: A "Unified" Theory

From the point of view of the *professions*, C-K theory proposes as unified a language as possible to facilitate dialog between the major design professions, namely designers, engineers and architects, independently of the specific nature of the objects they design and handle. The theory, ultimately known under the slightly enigmatic name "C-K", was initially presented as the "unified theory of design" (Hatchuel and Weil 1999).

In particular, C-K theory aims to combine the creative logic claimed by the artist with the logic of modeling and the creation of knowledge claimed by the engineer (or engineer-researcher). We might say that the theory seeks to combine two creative logics: that of the artist, who claims an ability to "see" new worlds, and that of the engineer, who claims an ability to create new knowledge. In practice we often find that these two approaches are far too simplistic, and that engineers can be visionary just as artists can be "savant"; C-K theory seeks precisely to formalize these two logics, that of the unknown made thinkable (the logic of C-space, concept space) and that of the regeneration of knowledge (the logic of K-space, knowledge space) and especially their interactions (the operators linking C and K).

#### 4.1.1.2 From the Point of View of Formalism: A Formalism for "Radical Creativity"

As with any theory of design, C-K theory tackles situations where $D(X_x)$ such that $P(X_x)$ is true is such that $D(X_x) \not\subset K(X)$ (see introductory chapter—this means that the initial knowledge *does not* include a set of decisions that enables X to have the property P(X)). But this time the aim of the theory is not to "minimize" the production of knowledge within the framework of a given dominant design. The theory must, on the contrary, reflect situations that show strong expansion of knowledge and reflect the design of objects deviating from hitherto known objects; furthermore, the theory should reflect the strongest forms of creativity, namely "radical originality" in the sense implied by Boden. As far as Boden is concerned, radically original ideas are those that cannot be produced by the set of generative rules whose purpose is to produce ordinary new ideas (Boden 1990, p. 40); hence this creativity explicitly assumes a revision of the rules, and the logic of this extension is not necessarily modular—they may lead to a radical questioning of the acquired knowledge and to a revision of definitions which hitherto seemed the most stable.

In this sense, C-K theory is a theory for the creation of new object definitions, a process consisting of two facets: first conceive the definition of hitherto unknown objects to bring them into existence, and then, on known objects, proceed to the propagation and re-organization required for the existence of the hitherto unknown new object while restoring or maintaining the conditions of existence of what had hitherto been known.

#### 4.1.1.3 From the Methods Point of View: Consider the Extension of FRs and DPs

C-K theory will seek to extend and complete known theories and methods, in particular theories and methods of rule-based design. The limit of the theories and methods of rule-based design can be simply characterized: they work well while the nature of the functions and design parameters is known (to refresh your memory, see the functional analysis workshop in Chap. 2, especially the "night-time bus-station in workshop 2.1"). These days innovative design demands regular revision and extension of the FRs and DPs. The theories seen for rule-based design call for no formal framework to consider these extensions nor for any rigorous method of getting there.

#### 4.1.1.4 From the Cognitive Point of View: Theories and Methods for Overcoming Fixation

For some time the cognitive sciences have shown the effects of fixation, where individuals in a creative situation that is both and individual and collective are victims (see (Jansson and Smith 1991; Ward et al. 1999; Mullen et al. 1991);

see (Hatchuel et al. 2011b) for a summary). This is associated in particular with a "fixed" representation of certain objects. For example, it is the effect of "fixation" that makes the puzzle below difficult to solve (see Fig. 4.1): how do you form a square by moving just one of the four matches arranged as in the figure? The solution is given on the right. We are conditioned to represent a square as a geometric form, and we fail to consider the "square" as in the sense of a mathematical operation.

Moreover, we can show that often the objective of training in industrial design these days is to overcome the effects of fixation. In this respect, they are inheriting the traditions of the Bauhaus: a study of the courses at the Bauhaus, in particular the introductory courses given by Itten, Klee and Kandinsky, showed the sophistication of the means used in training the young artists to overcome their fixations (Le Masson et al. 2013b). One of the expected results of C-K theory is in allowing the development of such methods—and (more modestly) in understanding the logic of existing methods.

More generally, and historically, the aim of the effort put into developing theories and methods of design was to correct any cognitive bias identified by the teachers and professionals of design. In the 1840s, Redtenbacher himself sought a method to prevent the designer of water wheels from always re-using the same wheel model without taking account of the context; the invention of systematic design also corresponded to a willingness to explore as much as possible, rather than be content with using only the available rules (see (Le Masson et al. 2011), also the historical case study in Chap. 2).

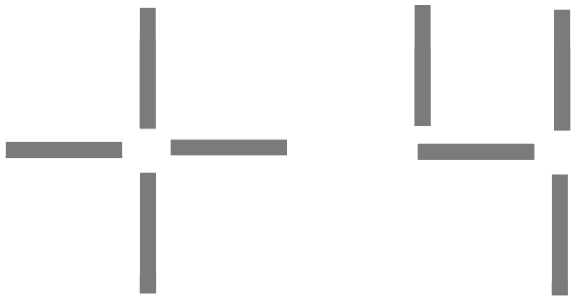

**Fig. 4.1** An example of fixation. Form a square by moving just one of the matches in the left-hand figure. The problem seems insoluble as long as we think of the square as a geometric shape. The problem is solved by recalling that a square may also be the result of the mathematical operation of raising to the power of two. Four is a square, whence the solution given on the right. Note that this example illustrates fixation, but is still hardly generative: of course, we are playing on the two definitions of a square, but these definitions do not have to be revised!

## 4.1.2 Main Notions: Concepts, Knowledge and Operators

### 4.1.2.1 Intuitive Motivation Behind the C-K Theory: What is a Design Task?

C-K theory focuses on one of the most troubling aspects of the theoretical approaches to design, namely the difficulty of defining the starting point of a design task, i.e. what professionals describe as "specifications", "programs" and "briefs". This involves describing an object by giving it only certain desirable properties without the ability to give a constructive definition of the object and without being able to guarantee its existence on the basis of pre-existing knowledge. While mapping type theories of design tend to equate design with research in a space that is indeed complex, not to say uncertain (but known), C-K theory tries to preserve the fact that it is the ambiguous, equivocal, incomplete or vague character of the starting point that will allow the dimensions of the mapping to be regenerated. C-K theory therefore suggests a model that allows the design of a desirable but unknown object whose construction cannot be decided using the available knowledge.

This intuition raises a number of problems: how to reason about an object whose existence is a priori undecidable? and how to model the changes in the knowledge base that the initial "brief" sometimes tries to revise? In a rigorous sense, the object exists only at the end of the design process; at the start it is hoped that this future object might have certain properties and it will then be necessary to "gradually construct the new, as yet unknown object whose existence is undecidable".

### 4.1.2.2 The Space of Concepts and the Space of Knowledge

The underlying principle of C-K is to model design as an interaction between two "spaces",[1] the space of concepts (C) and the space of knowledge (K), which does not have the same structure or the same logic. These two spaces (or more precisely, the logical status associated with the propositions which make them up) determine the fundamental propositions of the theory.

*Definitions of C and K*

**Definition of K space**: the propositions of K space are characterized by the fact that they *all have a logical status* (true or false).

**Definition of C space**: C space is the space in which as yet unknown objects are developed. The propositions of C space focus on objects whose existence is still undecidable on the basis of the propositions available in K. We say that *the*

[1]In theory, a "space" is a collection of propositions; spaces are characterized by the nature of the logical status of their propositions and by the nature of their mutual relationships.

*propositions of C are undecidable with respect to the propositions in K space*. These propositions are known as *concepts*. Propositions such as "there are boats that fly", "there are mobile bus stations" (see workshop 2.1 Chap. 2), " there are smiling forks", "there are effortless bolt croppers" (see workshop 3.2 Chap. 3) are concepts. A concept is an *interpretable* proposition (all the terms used are referred to in K space) that is undecidable with knowledge in K space: the proposition is neither true nor false. It is not possible to say that there exists a boat that flies (otherwise the design would cease), but neither is it possible to say that no boat that flies can exist (otherwise the design would also cease).

*Example*: Let us give a mathematical example: suppose that the knowledge space of a young mathematician includes only reals as knowledge about numbers. If one assumes that this young mathematician is not a designer, he will assume that it is impossible to take the square root of a negative number since the numbers available to him all have positive square roots. This means that, in K space, he actually accepts a proposition of the form "all numbers are real" (*sub specie aeternitatis*). Suppose now that this mathematician becomes a designer. Hence when he says: "there exist real numbers whose square is negative", for him, this proposition is an undecidable concept with respect to his knowledge space. Actually, it means that his knowledge space contains the proposition that "all numbers *known to me* are real" (and not the proposition "all numbers are real"). We shall return later to this example when dealing with the design of complex numbers.

Note that concepts are not necessarily "surprising"; designing a camping chair that is cheaper and lighter than all other known chairs is also a concept. This means that, excluding special cases, a functional set of specifications such as those used in systematic design, is a concept.

### *Structures of C Space and K Space*

**Structure of C**: concepts are of the form "*there exists a (non-empty) class of objects X for which a group of properties* $p_1$, $p_2$, $p_k$ *is true in K*".

In C space, since the proposition is undecidable, the proposition can only be worked on by *comprehension* (addition of properties) and not by extension (working directly on one or more elements in the class).

The structure of C is therefore constrained by the fact that the concept is an undecidable proposition. The most recent work proposes two approaches for the structure of C:

1. A set-wise approach: a concept can be considered as a particular kind of set, known as a C-set, for which the existence of an element is undecidable. This is the essential idea behind C-K theory and indeed the most critical aspect of its modeling. It is obvious that assuming the existence of an element in the C-set contradicts its status of concept (since we would then have to talk of elements with no possibility of defining or constructing them, contradicting the standard

elementary approaches of set theory (Jech 2002; Dehornoy 2010)). Also, the propositions that "a C-set is empty" or "a C-set is non-empty" cannot be decided with K. Only when the design has been completed can this question be answered. Technically speaking, Hatchuel and Weil suggest the C-set be governed by axioms using the axioms from set theory, rejecting those axioms which presuppose the existence of elements, namely the axiom of choice and the axiom of regularity. More generally, it is not possible in C space to have an inclusion relation, this relation having meaning only from the instant at which the existence of elements is proven. Rather, we shall speak of partial order (see below).

2. A logical approach: Hendricks and Kazakçi (2011, 2010) studied an alternative formulation of the C-K theory based only on first order logic, and which does not refer to C-sets. They obtained similar results on the structure of design reasoning.

In the remainder of this book we shall generally be using the set-wise approach, likening a concept to a set and the structure of C space to a set-wise structure without the axiom of choice.

**Structure of K**: the structure of K is a free parameter of the theory. This corresponds to the fact that design can use any type of knowledge, but also all types of logic, true or false; K can be modeled using simple graph structures, rigid taxonomies, flexible object structures or specific topologies (Braha and Reich 2003) or Hilbert spaces if there are stochastic propositions in K. The only constraint, from the point of view of C-K theory, is that propositions with a logical status (decidable) might be distinguishable from those that are not decidable.

Hence the K spaces of an engineer and a designer might be very different, with that of the designer containing, for example, knowledge about emotions, perception, theories of color or materials, etc., Such knowledge will clearly influence the way the (industrial) designer or engineer designs things. However, from the point of view of design, the models of reasoning are the same.

#### 4.1.2.3 The Design Process: C-K Partitions and Operators

Design starts with a concept $C_0$, an undecidable proposition with knowledge in K space. The issue with the theory is that of formalizing the manner in which this undecidable proposition becomes a decidable proposition. This can come about through two processes: a transformation of the concept, and a transformation of the knowledge space to be used to decide on the concept. Transformations continue until they come up against a proposition derived from $C_0$ that becomes decidable in $K'$ (i.e. K as it was at the instant the decidability of the concept was studied, i.e. when proof of existence is obtained). The concept then becomes a true proposition in K, and is no longer a concept.

During the process, the spaces evolve via expansions in K and partitions (or departitions) in C.

*Expansion of K, Partitions of C*

**Expansions in K**: it is possible to expand the K space (by learning, experimentation, remodeling, etc.); this expansion can continue until a decidable definition for the initial concept is obtained in K.

**Partitions in C**: it is possible to add attributes to the concept to promote its decidability. This operation is known as *partition* (see below). In C-K theory, the partitions of a concept $C_0$ are the classes obtained by adding properties (from K space) to the concept $C_0$.

If $C_k$ is: "*there exists a (non-empty) class of objects X for which a group of properties* $p_1, p_2, p_k$ *is true in K*", then a partition consists of adding to property $p_{k+1}$ to obtain the concept $C_{k+1}$: "*there exists a (non-empty) class of objects X for which a group of properties* $p_1, p_2, p_k, p_{k+1}$ *is true in K*". If $C_{k+1}$ is the result of a partition of $C_k$, we say that $C_{k+1} > C_k$. Hence we have a partial order between the successive partitions of a concept (note that in a set-wise approach without the axiom of choice, we might speak of in inclusion relation $C_{k+1} \subset C_{k,}$ though this relation should be constructed in accordance with the above principle and not according to an element-based logic).

Partition presents a rather specific problem: what is the status of the new $C_{k+1}$? This status must be "tested", i.e. its decidability with respect to the K space must be studied. This corresponds to making prototypes, mock-ups and experimentation plans. In turn, these operations can lead to expansions of the K space that are not necessarily related to the concept being tested (surprise, discovery, serendipity, etc.). The test has two possible results for $C_{k+1}$: (1) either $C_{k+1}$ turns out to be undecidable with respect to K and the proposition therefore becomes a K space proposition, and the design ends in success; or (2) $C_{k+1}$ remains undecidable in terms of K and the proposition is in C space.

*Example*: let the concept be "a boat that flies"; the designer is aware of flying fish and obtains, via partition, the concept of "a boat that flies like a flying fish". This concept must be tested in K (the test may consist of answering the question: do there exist boats that fly like flying fish?). The test will (probably) have two results:

- to proceed to the test, exploration in K will demand reflection on the flight of flying fish and hence will lead to an expansion of knowledge on this topic (e.g. modeling the flight of a flying fish).
- once this knowledge has been acquired, it will be possible to proceed to the corresponding test. Exploration in K may turn up boats that fly "like flying fish" (cf. Tabarly's hydrofoil) or otherwise (e.g. if one does not think that the hydrofoil flies exactly like a flying fish).

We may observe that the C-K partition does not exactly correspond to the definition of partition in mathematics: the status of undecidability does not allow the construction of a complete family of disjoint propositions whose "union" might reflect the previous concept.[2] Hence the $C_{k+1}$ stated previously will correspond to the concept $C_k$, but also the concept: "*there exists a (non empty) class of objects X for which a group of properties $p_1$, $p_2$, $p_k$,* ***but not-$p_{k+1}$****, is true in K*". However, another concept cannot be excluded, that might be: "*there exists a (non empty) class of objects X for which a group of properties $p_1$, $p_2$, $p_k$, $p_{k+1}$, AND not-$p_{k+1}$ is true in K*". We cannot have the law of the excluded third (*principium tertii exclusi*) in C space. However, the dichotomous logic ($p_{k+1}$ on the one hand, non-$p_{k+1}$ on the other) is often effective in C-K (see the workshop in this chapter).

*Operators*

All the operations described in C-K theory are obtained via four elementary operators representing the internal changes within the spaces (K ➔ K and C ➔ C) and the action of one space on another (K ➔ C and C ➔ K) (see Fig. 4.2 below for the four operators).

1. In C-K theory, the classical operations of inference, deduction, decision, optimization, etc. are operations of K in K.
2. The operator K to C is known as the *disjunction* operator, and consists of creating a new undecidable proposition on the basis of decidable propositions in K. The formulation of an initial $C_0$ is thus the result of a disjunction. In the same way, a partition ending up with a proposition $C_{k+1}$ that, once tested, is a concept and also a disjunction.
3. The operator C to K is known as the *conjunction* operator, and consists of creating decidable propositions on the basis of undecidable propositions. For example, we have seen that a test might lead to the creation of new knowledge. In particular, a conjunction is a concept that has been partitioned to the point that it has become decidable. This conjunction corresponds to a "design path" that goes from the initial concept $C_0$ to a proposition $C_k$ such that $C_k$ is decidable in K. Note that if $C_k$ is of the form "*there exists a (non empty) class of objects X for which a group of properties $p_1$, $p_2$,... $p_k$ is true in K*" is decidable, then all $C_i$ such that $C_k > C_i$ (in the sense of the order relation defined above, hence $i < k$) are also decidable and hence are in K.
4. The operator C in C is an operator that generates undecidable propositions on the basis of other undecidable propositions, using only C propositions; this is

[2]It is possible to retrieve, in design theory, the usual idea of partition in mathematics, we always need to introduce an "other" category and check that the intersections between the various alternatives are indeed empty.

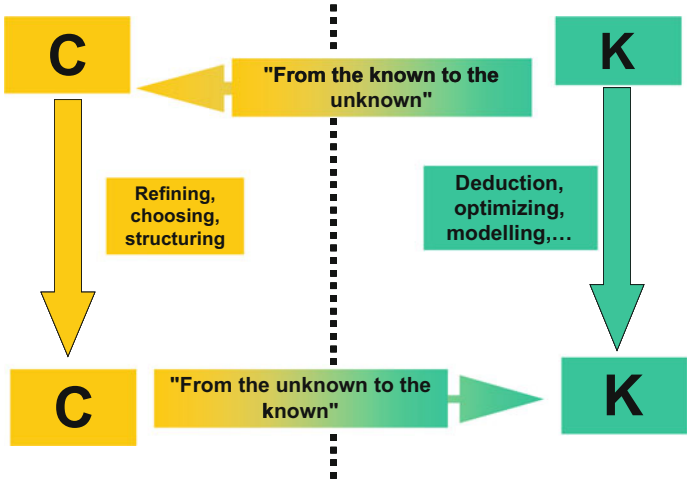


**Fig. 4.2** The four operators in C-K theory: C ➔ K, K ➔ C, K ➔ K, C ➔ C

used, for example, if we seek to obtain as complete a partition as possible. If we have the concept "*there exists a (non empty) class of objects X for which a group of properties* $p_1$, $p_2$, $p_k$ *is true in K*", the operator C ➔ C will enable the concept "*there exists a (non empty) class of objects X for which a group of properties* $p_1$, $p_2$, *non-*$p_k$ *is true in K*".

The main ideas of the theory are summarized in the Fig. 4.3.

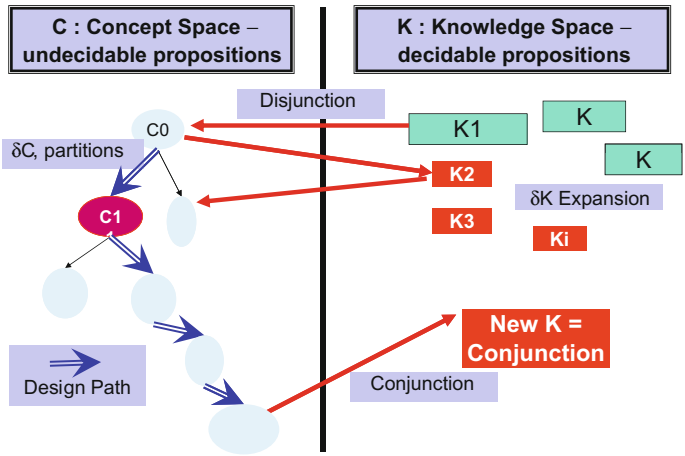


**Fig. 4.3** The main ideas of C-K theory

## *4.1.3 Main Properties*

### 4.1.3.1 Tree-Structure of a Concept $C_0$

One of the immediate results from C-K theory is that of showing that, for a given $C_0$, the C space necessarily has a tree-structure (associated with the order relation created by successive partitions).

This result is not trivial: it shows that the structure of the unknown (more precisely, the unknown thinkable with the propositions) is very particular. This means, for example, that if a brainstorming session is held on boats that fly, the set of ideas (each idea being likened to a concept) might be ordered as a tree structure based on the concept $C_0$.

### 4.1.3.2 Restrictive and Expansive Partitions

C-K theory allows us to distinguish between two types of partition: restrictive partitions and expansive partitions.

*Properties of Known Objects*

To this end an additional structure has to be introduced into K: properties common to the known objects. Given a family of objects X we can consider properties common to all objects X. This is what gives them their "identity" at a given instant (see the idea of the revision of identity of objects).

Note that we have avoided using the idea of "definition" here: these common, identifying properties do not constitute a general (fixed) definition of the objects. On the contrary (as we shall see) the identifying properties considered here can be "captured" from the perspective of their revision, rather than from their stabilization.

*Examples:*

- Hence in the case of complex numbers, we can say that, for the young mathematician, "all known numbers (the real numbers) have magnitude, namely their position on the real line".
- Similarly, for the designers of the boat that flies, we can say that "all known boats have a hull", and can even say that all boat hulls are of type A or of type B (wood, metal, etc.).
- For the designer of the camping chair (cheaper and lighter), all camping chairs have legs.

*Restrictive Partition*

A restrictive partition is a partition that makes use of these "identifying" properties of the known object or is compatible with them. Thus, in the design of a boat that flies, this can be partitioned into "a flying boat with a hull" (then to "a flying boat with a hull of type A" and "a flying boat with a hull of type B"). This operation is restrictive in the sense that it functions as a gradual selection in a set of known properties of the object "boat"—however, the concept thus formed remains a concept (of course we recognize that it is not enough to say that "the flying boat has a hull" to make it exist, to create a conjunction: undecidability still remains). The restrictive partition functions as a constraint: it obliges the flying boat to share an additional property with some of the known objects (namely the objects in the selection). Similarly, we can design a "two-legged cheaper and lighter camping chair", etc.

*Expansive Partition*

By contrast, an expansive partition is a partition that makes use of attributes that are not compatible with the identifying properties of the known objects (a flying boat without a hull or a flying boat with a hull that is neither of type A nor of type B; a number that might not be defined by its magnitude on the real line, etc.; a legless cheaper and lighter camping chair). Expansive partitions have two roles:

- they lead to *revision of the definition of objects*: if the "flying boat without a hull" ends up with a conjunction then there will exist in the new K space boats with and without hulls, so requiring the definition of a boat to be revised. In the case of complex numbers, we know that the conception of a number with a negative square leads to the creation of complex numbers that are not defined by their magnitude on the real line. Complex numbers require the previous definition of numbers to be revised.
- They steer the exploration towards new knowledge that is no longer deduced from the available knowledge. Hence working on the design of a "cheaper and lighter legless camping chair" can lead to experimentation: take a chair, cut off its legs and study the situation thereby created (See Fig. 4.4). We might discover that being seated on the ground raises new problems of balance-problems that were unknown with chairs with legs (whatever their number). It might lead to establishing a model of seated equilibrium in which balance might be ensured by the chair but also by the person on it, or by the interaction between the chair and the seated person. Hence we will have an operation in which new knowledge is created, driven by the expansive concept (see the chair example illustrated below). Thus is modeled a process by which the desirable unknown pushes to create knowledge, i.e. the imaginary stimulates research.

The generative power of C-K theory (discussed more formally further on) relies on this combination of the two effects of expansive partitions. Causing disruption with the definition of objects allows the potential emergence of new objects and the promise of new definitions; however, since their existence in K must still be brought about, expansive partitions lead to the creation of new knowledge steered by the disruptive concept (Fig. 4.4).

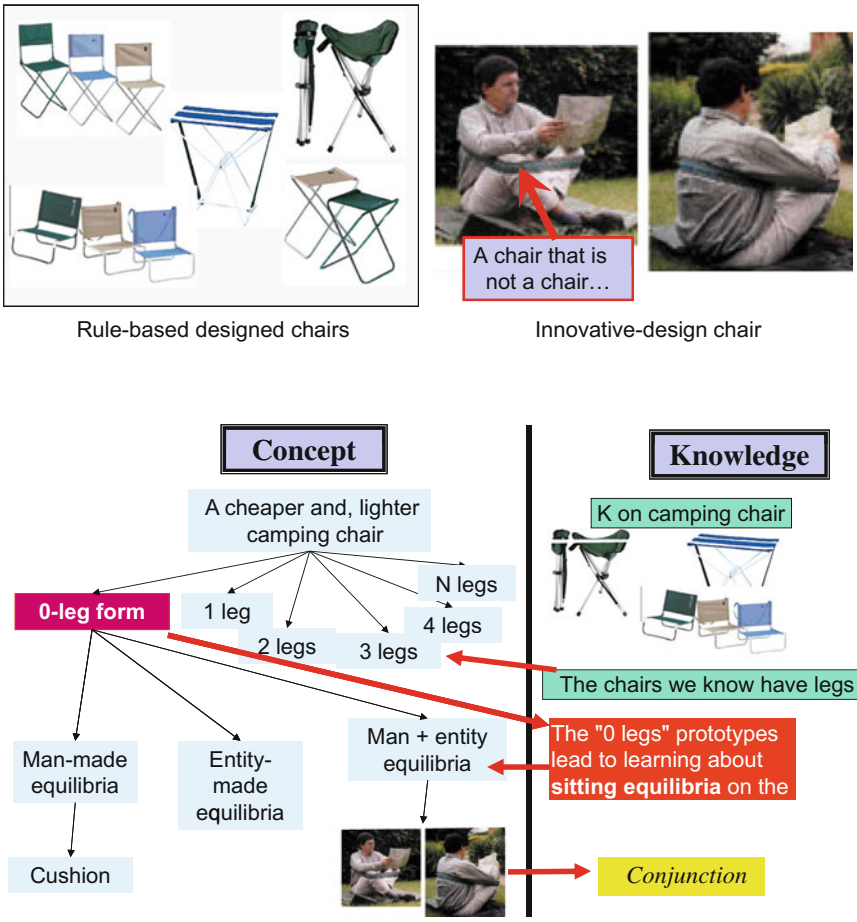


**Fig. 4.4** Designing a cheaper and lighter camping chair. C-K theory allows a rigorous process of reasoning resulting in the so-called "Sangloyan" of Le Vieux Campeur or the Chairless of Vitra design; it also enables the systematic design of other "neighboring" objects sharing the definition of a legless, cheaper and lighter camping chair

*Crazy Concepts—Chimera*

The idea of the expansive partition thus captures what we normally call imagination, inspiration, analogies or metaphors. These ingredients of creativity are well known, but their impact on design is not easy to assess and seems to verge on the irrational. C-K theory models their effect as expansive partitions and reveals a double effect, namely the possibility of new object definitions, and giving rise to the creation of new knowledge. By distinguishing between these two roles and the value of their interaction and superposition, C-K theory explains the design rationality of "crazy concepts" and "chimera".

In particular, we may observe that only the second effect can be preserved: the attempt at a new definition comes up against a dead end; even so, the explorations made will have created interesting knowledge for future exploration even though they may not be aiming for such a radical revision as the definition of the object. This expansive partitioning is not the same as a standard trial and error process since, in contrast to standard trial and error tests, "crazy concepts" are not selected from a previously known list but are generated by expansion. The knowledge acquired is not related to an "error" but rather to an exploration down a deliberately original path, a path for which a realistic or possible solution could not have been known in advance.

#### 4.1.3.3 New Objects and Preservation of Meaning

Expansive partitions raise a difficult question: if the expansive partition ends with a conjunction, then the new object will require that the definition adopted for the previous known objects be revised. The design of complex numbers requires the revision of what we know as a number: this is no longer a magnitude on the real line but an element in a commutative field. However, this revision itself means that others must be revisited as well (functions of a complex variable, new approaches to analysis, etc.). In revising the definitions, inconsistencies between all the former objects in K and the new objects must be avoided. Design thus implies a rigorous re-ordering of the names and definitions in K to preserve the meaning and definition of new and former objects.

**Main definitions and first results in C-K theory (See also Fig. 4.5)**

1. A set of propositions having a logical status is known as **K space**.
2. The addition of a proposition in K is known as an **expansion of K space**.

   By definition this proposition has a logical status

3. Given a K space, a proposition of the form {x, P(x)}, interpretable in the base K (P is in K) and undecidable in base K (P is in K), is known as a **concept** (the proposition {x, P(x)} is neither true nor false in K).
4. The addition of some supplementary property to the concept (which becomes {x, P(x), $p_k$(x)}) is known as a **partition**.

   Remark: C is K-relative.

   In a set-wise approach, a concept is a set from which no element can be extracted

   Theorem: a concept space has a tree-structure.

5. Given a concept and its associated base K, an **operator** is an operation (using K or C) consisting of transforming a concept (partition) or of transforming the K space (expansion).

   Primary operators: C ➔ C, C ➔ K, K ➔ C, K ➔ K.

6. A **disjunction** is an operator K ➔ C: passing from decidable propositions to an undecidable proposition (using the known to work in the unknown).
7. A **conjunction** is an operator C ➔ K: passing from an undecidable proposition to a decidable proposition (using the unknown to expand the known)
8. Given a space K and C ({x, $P_1P_2 \ldots P_n$(x)} on this space K, an **expansive partition** (conversely **restrictive**) is a partition of C making use of property $P_{n+1}$ which, in K, is not considered to be a known property associated with X (nor with any of the $P_i$, $i \leq n$) (conversely a property $P_{n+1}$ such that $P_{n+1}$ is associated with X in K or there exists an i, $i \leq n$ such that $P_i$ and $P_{n+1}$ are associated in K).

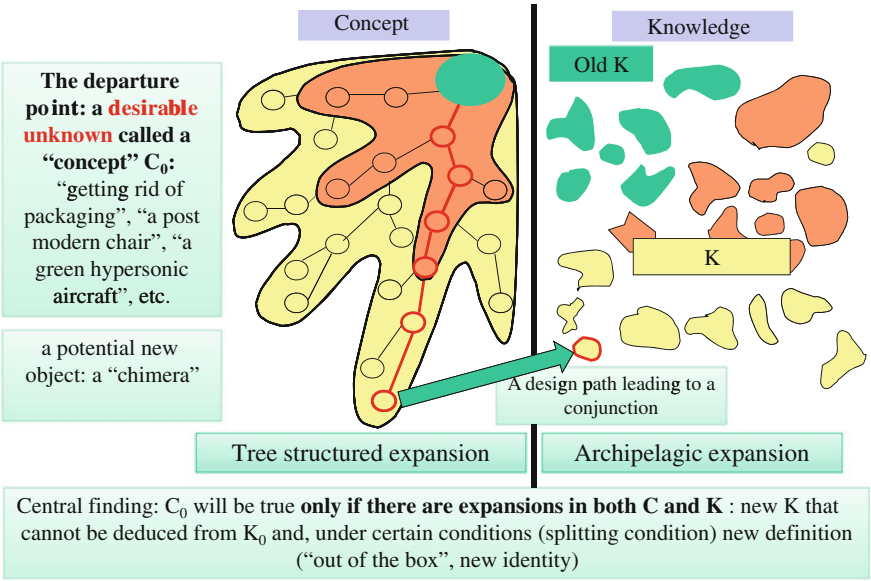


**Fig. 4.5** A Synthesis of main notions of C-K theory

## *4.1.4 C-K Theory and Other Theories of Design*

### 4.1.4.1 C-K Theory and Systematic Design

It can easily be verified that systematic design can be represented in C-K theory (see Fig. 4.6). We observe that systematic design consists of the a priori definition of partitions (partitions for functional, conceptual, embodiment and detailed design) and the types of knowledge to be invoked at each level, in addition to the nature of the knowledge to be produced at each stage.

In other words, in C-K the generative model appears as sequence of operators and the conceptual model as a set of items of knowledge—the theory allows the profound difference between these two ideas to be understood.

Recent work has analyzed several theories of rule-based design using C-K theory (Le Masson and Weil 2013) and has shown that, historically speaking, theories of rule-based design have always sought to preserve a strong conjunctive power while increasing generative power.

The representation of systematic design in C-K also emphasizes C-K's contributions with respect to systematic design:

1. *In C-K theory, design does not necessarily begin with functional language*. Hence the design of the cheaper and lighter camping chair starts with the number of legs, which pertains to the language of embodiment in systematic design.
2. In C-K theory it is possible to *revise the definitions of objects* in K. Hence the design of the legless chair is not constrained by the definition of a chair (chairs have legs).

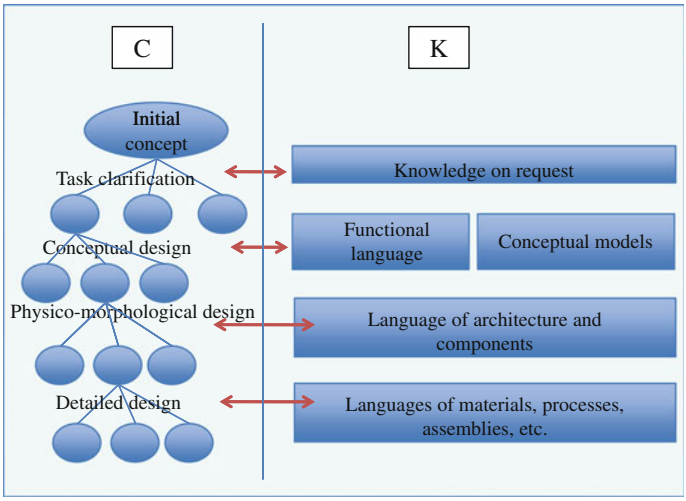


**Fig. 4.6** Systematic design represented in C-K formalism

3. This revision of definitions may focus in particular on the languages of systematic design themselves and hence lead to their revision. This is one of the expected consequences of C-K theory: *revising the list of known functions and the list of known DPs*. This revision might take the form of a (modular) add-on. However, in directing the logic of the revision of definitions towards the languages of objects appearing at each level (functional, conceptual, embodiment, etc.), C-K theory offers a rigorous method for redefining entire segments of these languages. For example, if the purpose of a chair is to be "comfortable", it is possible to work on the concept of an "uncomfortable cheaper and lighter camping chair" that would certainly lead to a revision of the functions of a chair; similarly, if the basic technology of a refrigerator is a two-phase thermodynamic cycle, C-K theory allows for working on "a refrigerator concept which does not operate according to a two-phase thermodynamic cycle".

#### 4.1.4.2 C-K Theory and Other Formal Theories: Generativeness and Robustness

While C-K formalism allows the extension of FRs and DPs to be considered, other theories of contemporary design obtain a similar result via different processes. It is instructive to reposition C-K theory in what appears today as a *continuum of formalisms as a function of their generativeness.* We shall provide a brief presentation only—for a more complete treatments, see Hatchuel et al. (2011a).

We start by one of the most sophisticated formalisms that appeared in the 1980s, the "General Design Theory" (GDT) of Yoshikawa (Reich 1995; Takeda et al.

1990; Tomiyama and Yoshikawa 1986). Design is represented as a mapping between FR and DP (as for Suh's axiomatic approach); one of the major inputs is that of formalizing the structure of the relationships between DPs and FRs as a function of knowledge about the "entities", already known objects from the same family (or even, from the perspective of an "ideal knowledge", all objects yet to come): these entities are the resources used to generate the DPs and FRs and the relational systems between them. Designing something is therefore that of making a selection from a subset of DPs and FRs on the basis of known structures; one of the major results of GDT is showing that the space of entities is a Hausdorff space, though for any set of specifications expressed by the FRs in this space it would be possible to "design" (i.e. extract) a mapping using DPs corresponding to these FRs. The generative power of GDT is thus that of its initial set of entities—this is a combinatorial, rather than expansive, generativeness. If we take the example of designing a camping chair, GDT enables cheaper and lighter chairs to be designed by combining the elements of knowledge obtained from all past chairs.

Suh's axiomatic system (see Chap. 3) is also concerned with the mapping between FRs and DPs, but rather than following the structures in a Hausdorff entity space, it suggests the construction of an ideal mapping with a one-to-one correspondence linking FRs and DPs. As we saw in Chap. 3, the axiomatic theory is one of evaluation and not of process. Hence it does not provide a generative power higher than the initial FRs and DPs, although it can occasionally lead to the development of specific DPs to "diagonalize" certain excessively coupled situations. In the case of the chairs, one might be driven to design modular chairs separating, for example, the structure of the seating part for greater comfort and less weight.

Using GDT, CDP theory (Coupled Design Process) (Braha and Reich 2003) still operates on the FR-DP mapping but on this occasion introduces phenomenological relations linking certain FRs to certain DPs, but (and herein lies the originality of their contribution) potentially by way of parameters that were never at the underlying origin of the process. These new parameters will therefore become new FRs or DPs. These "closure" operations mark the transition from a set of initial FRs to a set of extended FRs, similarly for the DPs. Thus we have a process of possible extension, associated with the closure structures known to the designers. In the chair example, CDP can lead to a functional extension: the chair is also a table, a traveling case, etc. and the constraints associated with the chair's environment (chair and table, chair and transportation, etc.) are amalgamated by "closure" and become new FRs for the chair (see Fig. 4.7).

The logics of "closure" are extended by the theory of Infused Design (ID) (Shai and Reich 2004a, b: Shai et al. 2009): the theory makes use of duality theorems and correspondence between systemic models which detect local "holes" (voids, see also the relation between C-K and forcing). These voids tend to create new relations and define new objects, and are therefore powerful levers in the creation of new DPs and FRs. In the case of a chair, for example, when applied to the question they will enable very different structural principles to be explored (rigidity of inflatable structures, tensile structures, etc.) and thus also deduce new associated FRs.

Finally, C-K theory allows extensions via expansive partition, i.e. via partitions making use of properties that the new object does not have in its usual definitions. Whence the legless chair.

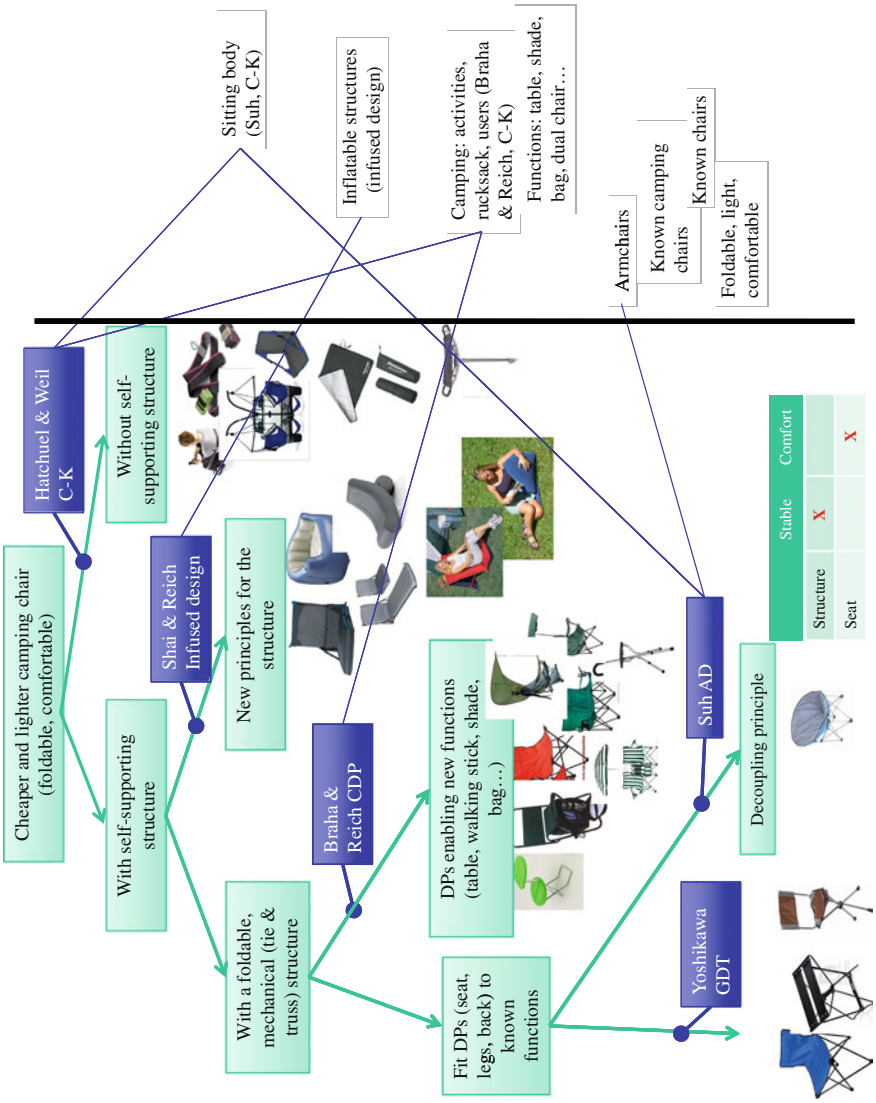


**Fig. 4.7** A continuum of theories of design for a variety of generative forms

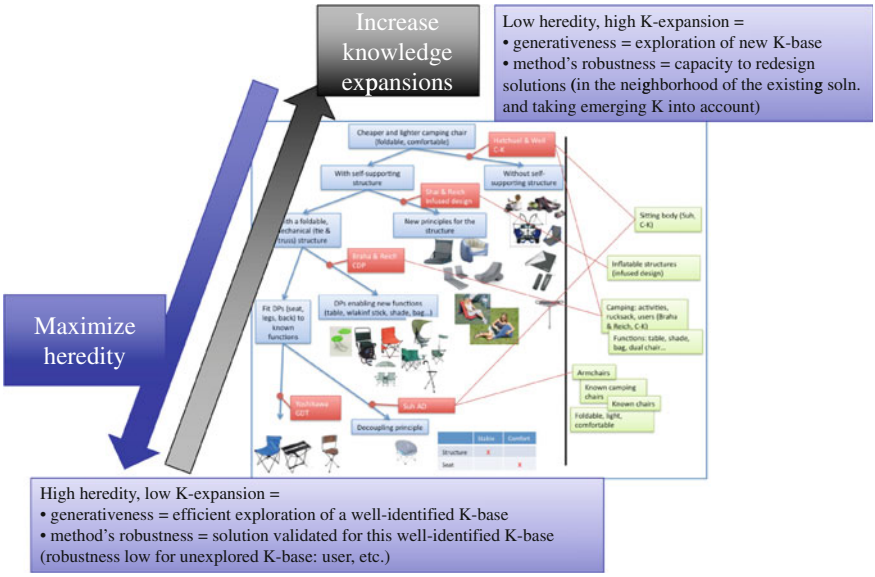


**Fig. 4.8** Heredity and generative power

Today we have an ecology of mutually complementary and reinforcing theories allowing reasonably powerful forms of extension for FRs and DPs (and more generally, object definitions). We therefore pass from theories that rely on well-formed structures in entity space (Hausdorff space, DP-FR relationship according to Suh) to theories of dynamic structures (extensions). We also pass from *generative power by combination* of known elements to a *generative power by extension* of the FRs and DPs, or even by extension of the definition of objects (Fig. 4.7).

It will be observed that these different strategies are also characterized by the weight given to what we might call "*heredity*": in GDT, we design on the basis of known objects, with generativeness depending on the exploration of original combinations, and robustness depending on the robustness of past designs. In C-K on the contrary, heredity is limited, not to say systematically reassessed (expansive partition) and robustness depends rather on the ability rapidly to create knowledge as a result of new questions (see Fig. 4.8).

#### 4.1.4.3 C-K Theory and Forcing: Theory of Design on Models of Sets in Mathematics

Armand Hatchuel has shown that, for objects, C-K theory is equivalent to the theory of forcing for models of sets (Hatchuel 2008, Hatchuel et al. 2013). In this more technical part (the reader less interested in formalism may skip this part), the

study of forcing, i.e. a mathematically high level of design, leads us to emphasize some of the properties of C-K theory.

A method, forcing, has been developed in (mathematical) set theory which creates (or designs) new set models responding to certain "desired" properties. This technique was developed by Paul Cohen in the 1960s to prove certain important theorems of independence, in particular the independence of the Continuum Hypothesis (CH) from the Zermelo-Fraenkel (ZF) axioms of set theory. Gödel had proved in the 1930s that ZF was compatible with CH by constructing a ZF model that satisfied CH. It was therefore necessary to conceive a ZF model that did not satisfy CH. Using forcing, Cohen constructed just such a model, and showed that he could construct as many reals as parts of $\mathbb{R}$ (which is a non-CH ZF model).

The design of these models with the aid of forcing is based on the logic of extension (see forcing discussions in (Hatchuel 2008; Dehornoy 2010; Jech 2002)): using an initial model M, a new model N is constructed containing M, and for which certain properties can be controlled. The construction of the field of complex numbers we covered in previous sections follows precisely a logic of extension (Cohen refers to this in his "intuitive motivations" (Cohen 1966)): starting with the field of real numbers $\mathbb{R}$ we construct an extension $\mathbb{R}[\alpha]$ stipulating that $\alpha$ is the root of the polynomial $X^2 + 1$ (in other words, $\alpha$ satisfies $\alpha^2 = -1$). The extension $\mathbb{R}[\alpha]$ contains all possible "numbers" constructed by addition and multiplication on the basis of the field $\mathbb{R}$ and $\alpha$, i.e. all "numbers" of type $a_n\alpha^n + \ldots a_1\alpha + a_0$. Put another way, the new numbers are described by polynomials with coefficients in $\mathbb{R}$. Indeed, $\alpha$ satisfies $\alpha^2 + 1 = 0$, hence some of these numbers are mutually equivalent (e.g. $\alpha^2 + 2 = (\alpha^2 + 1) + 1 = 1$ and similarly $(\alpha^2 + 1).(\alpha^2 + 1) + 1 = 1$, etc.) and it can therefore be shown that any new number is in fact equivalent to a number of type $a + b{\cdot}\alpha$ where $a$ and $b$ are in $\mathbb{R}$ and $\alpha$ satisfies $\alpha^2 + 1 = 0$ (we recognize the form of complex numbers where the common usage is to write $\alpha$ as $i$).

In Cohen's method, we no longer wish to construct an extension to a field (a very sophisticated set of mathematical objects) but rather an extension to models of sets (these are mathematical objects that are far more generic than a field). Cohen constructs this extension M[G] by adding to a model M a unique (generic) set G whose properties are specified by a partially ordered set P. The elements of P, called conditions, provide fragments of information about the set G whose addition has been proposed (just as we knew for $\alpha$, that $\alpha^2 + 1 = 0$). Typically, should it be proposed that a new subset G of N be added to M, one condition might be a piece of information of the type "3 is in G and 5 is not". Cohen showed *how to organize these fragments of information* to obtain new ZF models: in other words, forcing creates new sets but the properties of former sets are preserved, what might be called their "meaning". Even if forcing does not form part of basic engineering knowledge and is taught only in advanced set theory courses, it is such a general technique that it is possible to understand the basic elements, elements that will emphasize some important properties of C-K theory.

Let us see how to construct a new set G from M, but outside M such that M[G] preserves the "meaning" of M. Five elements are required:

1. a basic ground model M, a collection of sets, ZF model (equivalent to a K space in C-K)
2. a set Q of conditions defined on M. Each condition extracts a subset of M. A partial order, noted <, can be constructed on these conditions: if we let $q_1$ and $q_2$ be in Q we say that $q_2 < q_1$ if the subset extracted by $q_2$ is included in that extracted by $q_1$. Hence we can have in Q a series of compatible conditions of increasing refinement: $q_0, q_1, q_2 \ldots q_i$ such that for all i we have $q_i < q_{i-1}$. Such a series is known as a filter.[3] We may observe that a filter can be regarded as the gradual definition of an object by "constraints" $q$ where each constraint refines the previous one—a definition close to the successive partitions in C-K theory. We would imagine that the successive nesting of subsets of M could result in a set that is in M; surprisingly, as we shall see, certain nestings lead precisely to sets that are not in M.
3. The third elements: dense subsets. Given the set of conditions Q and the partial order <, we have (Q, <). We define a *dense* subset of Q, as a set D of conditions of Q such that any condition of Q is refined by at least one condition belonging to D. Put another way, even very long series of constraints (hence constraints associated with very "refined" subsets) are further refined by the constraints of D. Let $D_f$ = {the set of constraints satisfying a property $f$}, and assume that $D_f$ is dense. Whatever subset of M may be described by a condition $q$, this constraint is refined by $q$' satisfying $f$. This means that in any subset of M defined by the constraint $q$ there exists at least one included subset, defined by $q$' that refines $q$ and that satisfies $f$ (Any subset defined by a constraint such as $q$ at least "slightly satisfies" $f$; however, this does not mean that the whole set associated with $q$ has the constraint $f$), hence $f$ is a kind of "general property", "common" to any constraint $q$, even if this constraint $q$ is not itself in $D_f$.
4. The fourth element is fundamental: let G be a generic filter, i.e. a filter that intersects all dense parts. In the general case (and this is an essential property), *G is not in M*.[4] We take things "out of the box", as it were, creating an object that has a property constructed on the basis of the properties of objects in the box, but which no object can actually possess. Things are taken "out of the box" "from the inside". This is very close to an expansive partition: the property is constructed on the basis of the known (all the constraints of the filter G are known) yet it creates an unknown object. Why is G generally outside the box? Let us take an arbitrary object O in M, the part $D_O$ being defined by "the set of constraints that

[3]Filters are standard structures in set theory. A filter F is a set of conditions Q satisfying the following properties: it is non-empty, it is "upward-closed" (if $p < q$ and $p$ is in F then $q$ is in F) and it is consistent (if $p$, $q$ are in F, then there exists an $s$ in F such that $s < p$ and $s < q$).

[4]Actually, G is not in M the moment Q satisfies the "splitting condition": for any constraint $p$, there are always two conditions $q$ and $q'$ which refine it and which are incompatible (incompatible means that there will be no condition $s$ that will refine $q$ and $q'$ "further on"). Proof: (see (Jech 2002, Exercise 14.6, p. 223): suppose that G is in M and assume D = Q\G. For any p in Q, the splitting condition means that there exist $q$ and $q'$ that refine $p$ and which are incompatible; hence one at least is not in G and therefore is in D. Hence any condition in Q is refined by a constraint on D, and so D is dense. So G est generic and must therefore intersect D. Whence the contradiction. (see also Le Masson et al. 2016). For longer and more detailed explanations see Sect. 5.2.2.1, 199

are not included in this object O" is dense (for any subset—an arbitrary constraint q of Q—even very near to the object in question, always contains objects that are different from the object O; in other words, $q$ can be refined by some $q$' in $D_O$). Indeed, G intersects it hence there exists at least one constraint of G that distinguishes it from the object in question. This argument is the same as that of Cantor's diagonal. G differs from all sets M but at the same time G intersects all the "general" properties in M (i.e. all the properties valid for the constraints of Q, i.e. of subsets of M), G collects all information available on the subsets of M.

5. Finally, the new G is used to construct M[G], the extended model. This requires an operation known as "naming" that allows all new objects in M[G] to be described uniquely on the basis of the elements of M and G (all just as the complex numbers described above).

**Example: the generation of new real numbers** Cohen gives a simple application of the Forcing method: the generation of new real numbers from integers (see Fig. 4.9).

The ground model is the set of parts of $\mathbb{N}$

Forcing conditions: these are functions that, with any ordered finite series of integers (1, 2, 3,… $k$) associate with each integer a value 0 or 1, and hence associates the $k$-list with 0 and 1, e.g. (1, 0, 0…1). This condition is defined on the first $k$ integers and extracts among these first $k$ integers the subset of integers taking the value 1 via this constraint. We may also suppose that such a constraint corresponds to the set of reals written in base 2 and starting with the first $k$ terms (1, 0, 0… 1). Given a constraint of length $k$, it is possible to create a constraint of rank $k + 1$ which refines the preceding constraint while keeping the first $k$ terms unchanged and assigning the value 0 or 1 to the $k + 1$'th term. We thus obtain Q and the order relation <. Note that this order relation satisfies the splitting condition: for any condition: for any condition $q_k$, ($q$(0), $q$(1), … $q$(k)), there are always two conditions that refine $q_k$ and are inconsistent ($q$(0), $q$(1),… $q$(k), 0) and ($q$(0), $q$(1), … $q$(k), 1).

A generic filter is formed by an infinite series of conditions which intersects all the dense parts. The filter G contains an infinite list of "selected" integers and *is not in M*. We can prove this latter property by observing that Q satisfies the splitting condition; we can also present a detailed proof: let there be a function g in M (a function that associates a value 0 or 1 with any integer, i.e. a real number written in base 2) and let $D_g := \{q \in Q, q \not\subset g\}$, $D_g$ is dense in Q hence G intersects $D_g$ so G forms a new "real" number different from all the reals written in base 2!

The parallels between C-K theory and forcing are particularly valuable in that they allow certain characteristic features of design formalisms (for a more complete treatment and in-depth discussion of the relationships between C-K theory and forcing, see (Hatchuel et al. 2013)). Hence with forcing we find some aspects already highlighted with C-K theory:

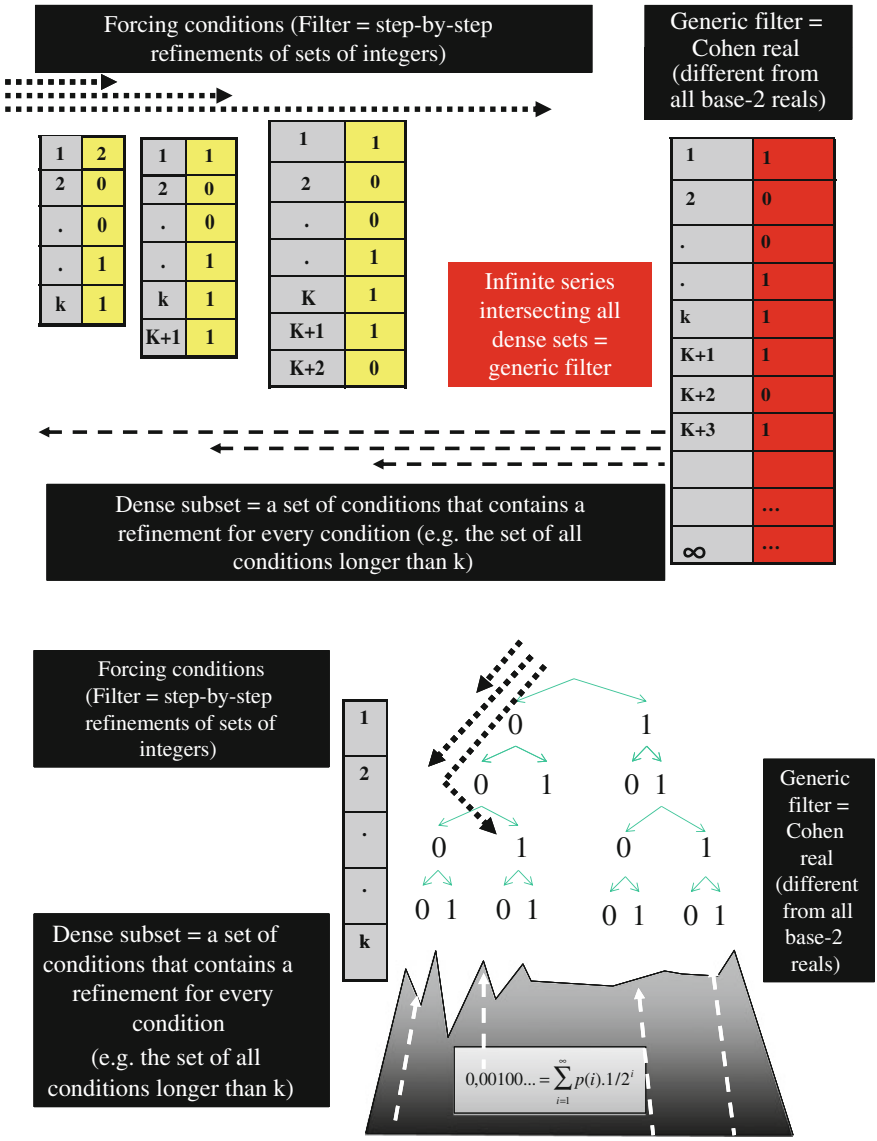


**Fig. 4.9** Two representations of the creation of new real numbers by Paul Cohen

1. Expansion processes: in C-K theory as in forcing, a new object is constructed via progressive refinements. Moreover, we can show that a "design path" ($C_0$, … $C_k$) in C-K corresponds to a generic filter.[5] For all that, the generation of new

[5]For the entire dense subset D in C space, there is a refinement of $C_k$ that is in D. $C_k$ is also in K (the first conjunction) hence any refinement of $C_k$ is in K and not in C, hence the refinement of $C_k$ is $C_k$ itself. Hence $C_k$ is in D. Hence $C_k$ does indeed intersect all the dense parts.

objects in C-K does not rely on an infinite number of conditions as in forcing, but on the existence of an expansion in K (introduction of a new proposition having logical status), even the revision of a definition in K. The two approaches differ in technique, but both depend on a logic of generic expansion.
2. Processes for preservation of meaning: the new objects created must remain consistent with past objects. Forcing imposes a "naming" phase on the process of generic expansion; C-K theory operates by "conjunction" of the progressive development of new propositions that are true in K space and by K-reordering.

The relationship between C-K and forcing also enables several other critical properties of a theory of design to be highlighted:

1. Invariant ontologies and designed ontologies. Forms of expansion are found in Forcing just as in C-K theory; however, forcing also tends to put the emphasis on structures *conserved* by forcing, hence the ZF axiomatic system is conserved from M to M[G}. In design, we will thus have an invariant ontology, a set of rules that remain unchanged over the course of the design; this ontology defines the conceived ontology by complementarity, i.e. the set of rules that can be changed by design (and there are a lot of them! We might imagine that a large part of human knowledge is constructed on such conceived ontologies); intuitively, we might think that the more general invariant ontology is, the more design would be generative—however, we might also think that a lack of stable rules would undermine the creative power of design.
2. Knowledge voids—independence and undecidability. In set theory, forcing allows the construction of set models that are ZF and satisfy a property P, and others that are also ZF but which do not satisfy P. We therefore show that P is undecidable in ZF or independent of ZF. P can be considered as a "void" in the knowledge over the sets; this void is in fact the condition for which forcing can be applied. In C-K theory, concepts are also undecidable propositions that can be viewed as "voids". The undecidability of concepts is assumed, and is necessary to start the design process. These "voids" are therefore common to both approaches, i.e. C-K theory and Forcing. Design "fills" the voids; forcing shows that "filling a void" is the same as showing the existence of independence structures in knowledge.

This idea of "void" also emphasizes the fact that *design is not based on the accumulation of knowledge, but on the existence of independence structures ("voids") in knowledge*.

### *4.1.5 Why C-K Theory Meets Our Initial Expectations*

While the presentation of C-K theory here is still relatively succinct, the reader can be assured that, using the elements given above, the theory meets the initial expectations:

- "Professional expectations": the theory enables the relationship between the K-oriented professions (engineering) and the C-oriented professions (design) to be considered; it also reveals that there is K in design (the designer's K spaces—but see also the most recent work on K structures in design (Hatchuel 2005b, 2013; Le Masson et al. 2013b) and C in engineering (see below the interpretation of systematic design in C-K).
- Formal expectations: taking note of the creative act: see the notion of expansive partition, heredity, conceived ontology, invariant ontology, etc.
- Methodological expectations: the theory allows the revision of object definitions, and hence the extension of FRs and DPs (see C-K theory and systematic theory, C-K theory and other theories of innovative design).
- Cognitive expectations: C-K theory enables the effects of fixation to be overcome: fixation will arise from the definition of certain objects; indeed, the theory allows these definitions to figure in K space, then to be rigorously and systematically rediscussed via expansive partitions in C (see also the C-K exercise in the remainder of this chapter workshop 4.2).

## 4.2 Performance of the Innovative Design Project

In this chapter we study the performance indicators of a project team responsible for an exploration in innovative design. We shall be following the logic of the canonical model (applied to a single project): we give the inputs and outputs of the innovative design and the associated measurement methods.

### *4.2.1 Fundamental Principle of Performance in Innovative Design: Giving Value to Expansions*

While systematic design gives value to minimizing expansions in order to attain a known objective, innovative design provides value to expansions. From a concept and a knowledge base we know that a concept tree and new propositions in K will necessarily be deployed; the concept structure is tree-like (see Sect. 4.1 of this chapter); In K space, the structure will generally be archipelagic in the sense that certain propositions will have no links with others (see Fig. 4.10).

In the exploration of "crazy concepts", this might give rise to new knowledge (expansions in K) which could be of value in the creation of a less original design path. Hence value must be given to the set of expansions in K and partitions in C.

In C-K, a rule-based design project minimizing the production of new knowledge will have the profile below. A "good" C-K exploration should rather tend to create "balanced" trees (exploration in "all" directions) and create new knowledge (see Fig. 4.11).

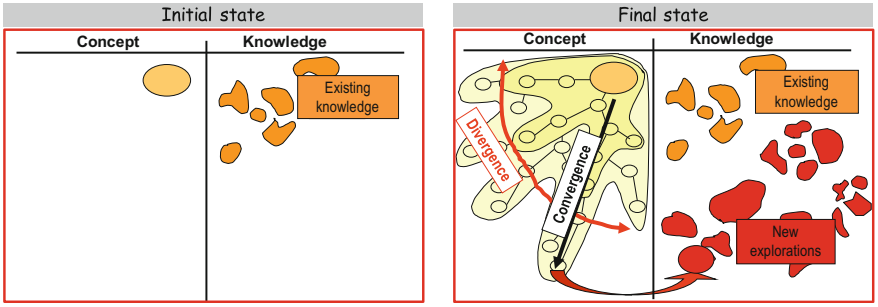


**Fig. 4.10** Inputs and outputs for innovative design reasoning according to C-K theory

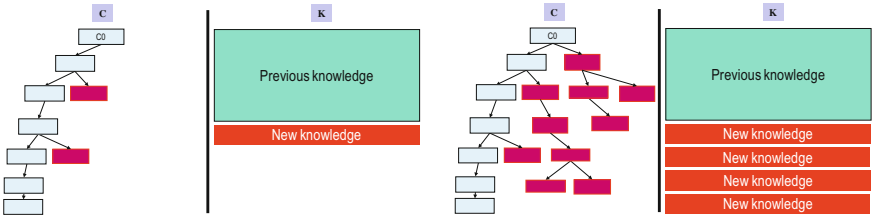


**Fig. 4.11** Schematic representation in C-K of a "good" rule-based design exploration (***left***) and a "good" innovative design exploration (***right***)

## *4.2.2 Outputs: V2OR Assessment*

How do we qualify a "good" tree and "good knowledge" in practice? C-K theory provides criteria for assessing outputs that allow an exit from an assessment restricted to the singular product without being confronted by the logical contradictions of knowledge for knowledge. Two families of criteria can be identified: those associated with C space and those associated with K space.

### 4.2.2.1 Criteria Associated with the Structure of the C Tree

For the C space, we draw inspiration from the assessments used for tests of creativity. One of the great contributions to psychological work on creativity (Guilford 1950, 1959; Torrance 1988) was the very early proposal for measures of creativity that would measure this form of intelligence differently from the traditional measure of IQ, but with the same rigor. For these authors, creativity is thus the ability to answer questions along the lines of "what can you do with a meter of cotton thread?"—questions for which there is no single good answer (as in IQ tests) but several possible answers. Measuring creativity is therefore that of *characterizing*

*the distribution of answers* given to this type of question. Historically, the criteria suggested are: fluency (number of answers), flexibility-variety (variety of categories used to answer) and originality (originality being measured with respect to the reference distributions obtained by giving the same test to other individuals). C-K theory is used to apply these criteria to the innovative project. Just two criteria are normally sufficient (the fluency criterion is not used):

- **Variety**: the variety of the proposed solutions is assessed. In tests of creativity we refer to previously constructed categories (for 1 m of cotton thread there will be ideas centered on measurement (meter), on the thread (flexibility, tension, etc.) and on cotton, for example). In the case of the innovative project, the a priori distribution is generally not simple; hence the assessment is constructed on the basis of the proposed tree (a posteriori): variety is therefore measured in terms of the number of partitions but also their potential ranking (long chains may be given value). Thus, value will be given to trees with many "long" branches spread out in numerous directions. On the other hand, trees on which there are many ideas but all going along the same lines (technical or functional) will score low in variety.
- **Originality**: creativity is measured by reference to a known distribution (the yardstick given by the average distribution of known distributions); actually, such a yardstick does not exist in situations involving an innovative project! Another known alternative consists of evaluating the solutions suggested by experts (see the CAT method, Consensual Assessment Technique, developed by Amabile 1996; Amabile et al. (1996)); however, quite apart from the process being rather expensive and difficult to implement for innovative projects, it is intrinsically limited since these experts themselves may be victims of fixation, leading them to fail to recognize what is in fact original (Agogué 2012; Agogué et al. 2012) or to consider paths to be original when they may not be. C-K theory enables a more endogenous measure to be constructed: it is sufficient to count the expansive partitions, i.e. the cases in which the project managers will consider that they themselves add attributes to the concept that are not standard attributes in the knowledge base. The assessment protocol therefore enhances the process since it forces these project leaders to clarify the redefinitions they have used.

*Examples* (for the reader to discuss) (these examples are taken from Gardey de Soos 2007): taking the case of the night bus station, a *collapsible* bus station is more original than a *comfortable* bus station; a *summer* metro station is more original than a *well-lit* metro station.

#### 4.2.2.2 Criteria Associated with K Space

It is not obvious how to assess the knowledge acquired: any project (especially a failed project) can show that it has created knowledge. The argument of knowledge creation is generally insufficient for a positive assessment of a project. Contenting

oneself with an assessment of the concepts and ideas would hardly reflect the value of the expansions that had been made (see Elmquist and Le Masson 2009 for more on this debate). To assess the knowledge produced, one criterion is to evaluate it *according to its contribution to some future rule-based design*. To a first approximation, we consider a piece of knowledge to be useful in a design if it satisfies one of the following conditions: either it is a proposition that enhances the functional language, or it is a proposition that enhances the design parameters, whence two criteria: one "value" criterion and one "robustness" criterion:

- **Value**: in rule-based design, value is normally obtained by validating the functional criteria previously set out in a requirements specification. In innovative design, the value of an exploration is the ability to create new knowledge about the stakeholders and their many and sometimes unanticipated expectations (opinion, leaders, specifiers, customers, residents, third parties). In other words, the value assessed here is not the value of an object that has validated a criterion but is simply the ability to identify a new assessment criterion, whether that criterion has been validated by a product of the project or not.

*For example* (still with the bus station, same source (Gardey de Soos 2007)): in a base K where the functional criteria of the bus station focus generally on the problems of transport, the proposition that "certain residents (associations, shopkeepers, municipal authority, etc.) have certain expectations of the bus station" is a proposition that represents an increment of value, hence it is a new piece of knowledge that increases the value of the innovative project.

- **Robustness**: in rule-based design, robustness is often seen as equivalent to the validation of a functional criterion as a result of some well-mastered technical solution. In innovative design, "robustness" increases when new technical principles are identified, i.e. the list of potential solutions is enhanced. Included here are the new conceptual models accumulated by the explorations.

Variety, Value, Originality, Robustness (V2OR) constitute alternative criteria to the CQT criteria.

#### 4.2.2.3 An Example: The RATP Microbus Project

In the 2000s RATP (*Régie Autonome des Transports Parisiens*) launched a new type of bus route, covering local routes and requiring buses that took up little space, known as microbuses. The first microbus project was considered a failure according to standard project management criteria—the project was delivered late, the new hybrid microbus was not ready when the line was inaugurated by the mayor of Paris, etc. However, an analysis based on C-K formalism and the V2OR criteria confirmed the intuition of the teams working on micromobility: the exploration brought by the first project was very rich in terms of V2OR and the outputs gathered at that time gave rise to many products and services that appeared later in the field of micromobility (see (Elmquist and Le Masson 2009) and see the Fig. 4.12).

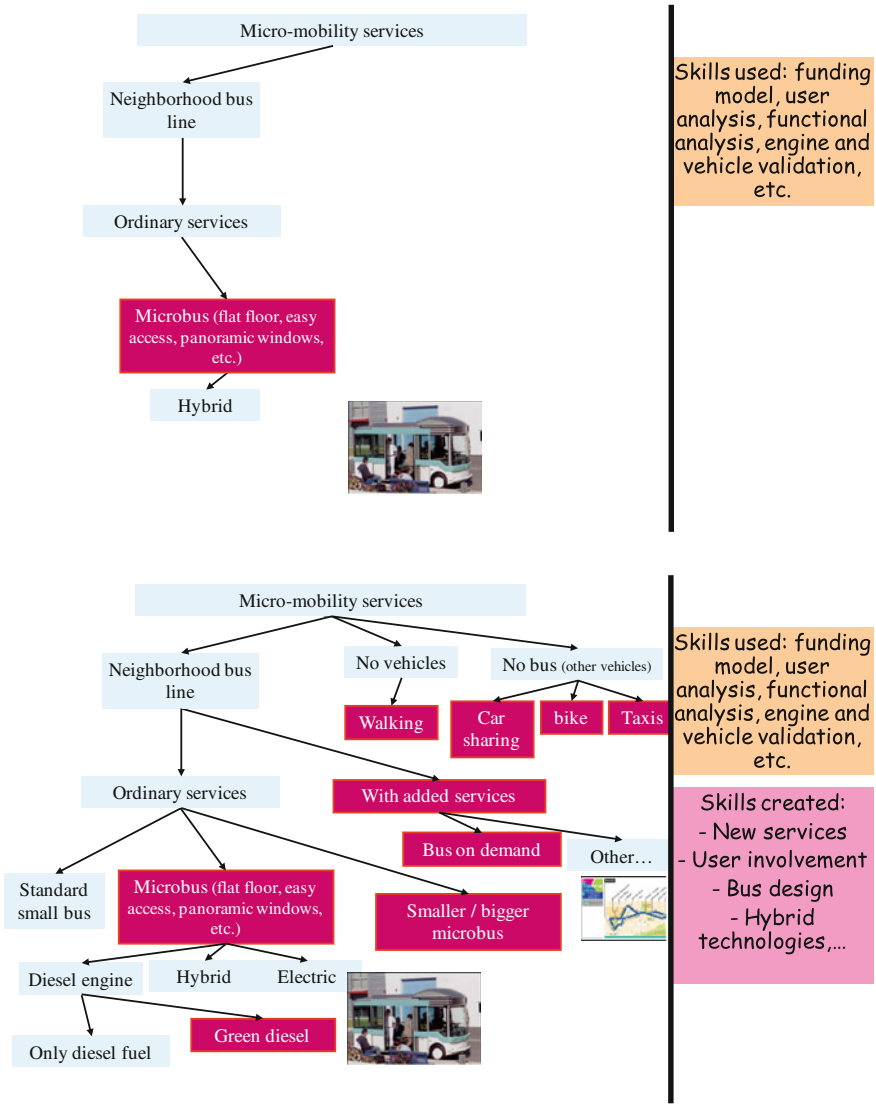


**Fig. 4.12** Assessment of an innovative project: keeping only the main path/keeping all learned items. Within the standard CQT context (inherited from rule-based design projects) the project is perceived as a failure: it consumes many resources for a limited result (the first microbus was delivered late and was not a hybrid). From a V2OR perspective, it turns out that the microbus project was able to make a very broad exploration of the field of micromobility and build resources into the ecosystem—resources that would later allow an entire range of micromobility products and services to take off. The microbus itself would evolve into a whole range of vehicles

### 4.2.3 Inputs: Estimation of the Resources Consumed in the Case of an Isolated Innovative Project

Formally, the primary input of design is the *initial knowledge* (the skill of the designers). Hence we can estimate these resources by their "cost of use", i.e. the designers' salaries. We are also familiar with the strategies for reducing the cost of these resources (externalization, open innovation, etc.), and we can envisage a certain input "quality" (level of skill, ease of coordination, activation, etc.).

Another less obvious input is the *initial concept*. It is hard to put a figure on this input but it can play a major role. One might be tempted to liken the concept to a "good idea"; however, a "good idea" is a rather ambiguous notion (Is this a feasible idea? Is there a market for the idea? Or is it an original idea?) while a "good concept" is simply a well formed concept (the lack of logical status is obvious); on the other hand, a "bad concept" is a poorly formed concept, equivalent to a piece of knowledge ("services for the elderly" is a bad concept: such services already exist; implicitly it almost certainly means "cheaper services for the elderly, 'better' services focusing on life at home, independence, etc.").

Finally, the last critical input: the *expansion procedures* necessary to operate between C and K. In innovative design, the production of knowledge is not marginal; the tools for producing knowledge are therefore a critical input. Essential resources also include the quality of browsers, scientific equipment, relationships with research laboratories, the design studio, and other knowledge and concept producers; the capacity for making prototypes and demonstrations, validation procedures and tests, etc.

### 4.2.4 The Logic of Input/Output Coupling

#### 4.2.4.1 Returns from Expansion and Returns from K-Reordering

Formally, input/output coupling can be complex. We recall that in the case of rule-based design, this coupling held to being the miracle of having "the competence of its products, and the products of its competence" (see Sects. 2.2 and 3.1). The "closer" the initial requirements specification (concept) was to the available knowledge, the better the performance (in a broad sense: not just conceptual models but generative models as well)—meanwhile allowing a marginal renewal of the rules, under the logic of dynamic efficiency.

In the case of innovative design, the logic of renewal becomes the most critical. A concept may be "far" from the knowledge base, but above all this "distance", this tension, must give rise to expansions and to a V2OR performance—at minimal cost. This efficiency is constructed in two parts:

- on the one hand, an efficiency in the phases of disjunctions and partitions in C (including the production of associated knowledge)—this is the most obvious efficiency.
- however, on the other hand performance is involved in the operations of conjunction and K-reordering: the "K-reordering" phase, i.e. the reordering of the knowledge base, may be fairly costly and reasonably "profitable" depending on the initial quality of the knowledge and successive partition strategies. This K-reordering phase is often critical for the efficiency of innovative design.
  - Examples of cost: certain disruptions can force an in-depth review of the skill necessary not just for the new product but also for all the preceding products (not just technical skills but also skills in production, distribution, commercialization, certification, branding, etc.). Hence, a new hypoallergenic filter system for the passenger compartment of automobiles may oblige all the pre-existing vehicles in the range to be revisited, or develop solutions for bringing previous vehicles up to date, etc.
  - Also an example of profitability: putting knowledge in order can "adorn" the value of previous products (Le Masson and Weil 2010): the Eiffel tower brought about an "adornment" of all existing iron architecture) (for the idea of "adornment" in design, see (Hatchuel 2006))

#### 4.2.4.2 Towards a Logic of the Constitution of Resources

We observe that outputs introduce a feedback loop on the inputs: acquired knowledge and stated concepts constitute resources for later designs. This leads to two remarks:

- *pending concepts are also resources*; the ability to draw on already "designed" imaginary items is a priceless resource. These "imaginary" items are sometimes part of the knowledge of experts (who not only understand the solutions that have been developed effectively but also all the dreams of some technical domain that have already been tested without success, or those that have simply been thought about) in the manner of mathematical "conjectures", "utopias" or "great technical challenges" (e.g. see the work on imaginary space ideas) (Cabanes 2013).
- if the innovative project creates resources, then we can take account of this future "revenue" in the initial allocation for the innovative project. A limited initial budget can be a wise and effective solution, provided the project is left to benefit from its own dynamic returns.

We see the *logic of repeated innovation* allowing teams to gradually build up their resources. We also understand that these logical processes exceed the "singular project", and we shall discuss them in greater detail in this Chapter.

## 4.3 Organization of an Innovative Design Project

First of all we shall examine aspects of coordination (processes, etc.) and then questions of cohesion.

### *4.3.1 Design Space and Value Management*

In rule-based design, linear reasoning made the process predictable and allowed it to be split into phases. Hence it supported stage-gate and planning. In innovative design, difficulties mount after the announcement of an initial concept $C_0$:

- The value associated with the concept may be poorly identified: "find a response to Toyota hybrid vehicles", "find applications for fuel cells", "find applications for natural fibers in construction" are possible concepts but their associated value remains to be explored (in contrast to the purpose of a normal requirements specification, which is to start with a "customer request").
- How to start the design process when the knowledge base is absent or obsolete? Expansions in K space are necessary, but where to begin? Even worse, sometimes the missing knowledge itself is not obvious, and it is the role of innovative design to reveal it. For example, the world specialist for petroleum drill pipes works on pipes "without lubricant": it would appear that it is simply a matter of finding a substitute for the contaminating lubricants used to facilitate screwing up drill pipes on offshore platforms—surely just chemistry of some sort? In fact, the project would reveal the necessity of working on the entire logistics of the pipe, on machining tolerances, the tools used by the fitter, the software used on the drilling rig, etc.
- How to avoid the premature death of the concept, surrounded as it is by obvious and apparently unsurmountable obstacles? How many innovative projects have ground to a halt simply because they were unable, right from the start, to demonstrate that they were satisfying some essential technical specification? In this case, the K base seems rich but a strong negative conjunction seems to have to come into play, linked for example to cost or draconian certification imperatives (e.g. demonstrating the airworthiness of an innovative drone).

Suppose reasoning gets under way and that the process starts, how do we explore without losing our way? How, during the exploration, do we avoid fixation or being attracted to "good ideas"? Reasoning does not occur in just one step. However, how do we define such steps, given that the definition of the steps results from successive learning processes?

C-K theory gives us the opportunity to identify the major difficulty: given an initial knowledge base K and a concept, the organization can only focus on the

(mathematical) operators.[6] Previous difficulties are all related to questioning the operators to be used. *The creation of knowledge (ΔK) and its use in reasoning in fact represent organization of the exploration of a field of innovation.*

Formally, the elementary design operators (C ➔ K, K ➔ K, K ➔ C, C ➔ C) need to be managed; the combination can be sophisticated, thereby corresponding to such design actions as simulating, modeling, testing, validating, discovering, building prototypes, calculating, optimizing, selecting, organizing a focus group, observe uses, etc. Organizing the process of exploration in a field of innovation consists of *making these elementary actions possible*.

This essential management purpose—the possibility of partitioning to explore a concept—is a design space. We shall define a design space as working space in which the learning processes necessary for design reasoning are possible (Hatchuel et al. 2005, 2006). Formally, it is a subset of the initial set $\{C_0, K_0\}$ *in which designers can learn what needs to be learnt for exploring the concept.*

**Design spaces in C-K formalism:** The definition of a design space can be set out within the framework of C-K formalism. A design space can be defined as a configuration $C_0^*$ - $K_0^*$ with a *clear link* to the initial $C_0$-$K_0$ configuration:

- *$C_0^*$ is linked to $C_0$ by changing the attributes of the same entity*: Given that $C_0$ is of the form "entity x with properties $P_1 \ldots P_n(x)$", $C_0^*$can be "entity x with properties $P_i \ldots P_j \cdot P_1^* \ldots P_m^*(x)$" where Pi…Pj are properties chosen from among $P_1 \ldots P_n$ and $P_1^* \ldots P_m^*$ are new attributes, chosen to support the learning process.
- *$K_0^*$ is a set of knowledge items which can be activated specifically within a design space* (pending expansion). Hence $K_0 - K_0^*$ is the knowledge base that may *not* be used by the designers working in the design space. It may seem strange that the design space *restricts* the K space to be explored. However, $K_0^*$ may also force knowledge to be implicated that might not be immediately activated in $K_0$.

The design process in $C_0^*$ - $K_0^*$ is always a double expansion $\delta C_0^*$ (new attributes added to $C_0^*$) and $\delta K_0^*$ (new propositions added to $K_0^*$). In other words, C-K formalism is still useful within a design space.

The link between the global $C_0$-$K_0$ and the design space is modeled by two types of transition operators. The first are operators going from $C_0$-$K_0$ to $C_0^*$ - $K_0^*$, known as *designation operators*; the others are the *extractions* made on the $\delta C_0^*$ and $\delta K_0^*$ to bring what is extracted into the $C_0$-$K_0$. context. The

[6]The temptation might be to "select" the favorable $C_0$-$K_0$ configurations. However, what would be the criteria for such a selection, to the extent that the value is precisely an expected result of the process? This is why the issue is rather, to control the exploration.

designation operators may consist of adding a few attributes to $C_0$ or adding knowledge to $K_0$.

C-K formalism is therefore useful in describing expansion processes not only at the global level (value management space working on $C_0$-$K_0$) but also at the level of each of the particular design spaces ($C_i^*$ - $K_i^*$).

**An example of design space: designing an innovative drone without studying any flight certification (Taken from SAAB Aerospace)**

The initial concept is $C_0$: "an innovative pilotless aircraft". However, the first design space is constructed on "an autonomous helicopter for the surveillance of automobile traffic" with research focusing on artificial intelligence and image analysis:

- $C_0$: "x = a flying vehicle", $P_1$ = "flight certified", $P_2$ = "pilotless", $P_3$ = "innovative".
- $K_0$: all knowledge is available or can be produced.
- $C_0^*$: remove $P_1$ and add $P_4$ = "being a helicopter" and $P_5$ = "for traffic surveillance duties".
- $K_0^*$: all knowledge about aircraft, military missions or automated flight is deliberately avoided. Why? Because normal drones are built on the principle of automated flight, which immediately determines the modes of reasoning. The design space explicitly excludes anything automatic in order to explicitly steer the learning process towards those disciplines that are underestimated in the world of drones: Artificial Intelligence (IA) (how an object can "decide" when faced with an original situation) and image analysis (what are the tools that can scan and analyze the environment)
- Validation in $C_0^*$ - $K_0^*$: validation is linked to the disciplines concerned, and air certification is not considered.

The design space "emerges" from a more global exploration process, and feeds this process in return. We shall call this space that initiates the design spaces and summarizes the learning processes the "value management" space. The relationships between the design and value management spaces are modeled by designation operators—constitution of the design space (and extraction)—and integration of the learning processes in the design space within the overall reasoning. These various ideas enable the process of exploration of a field of innovation to be represented as per the diagram below (Fig. 4.13).

This modeling process describes the actions to be taken when faced with any difficulties encountered in exploring the fields of innovation:

- The initial concept can be poorly stated, the disjunction is barely visible and the unknown is hardly desirable. This is a poor point of departure for design reasoning. It is then possible to launch an exploration of a concept derived from the

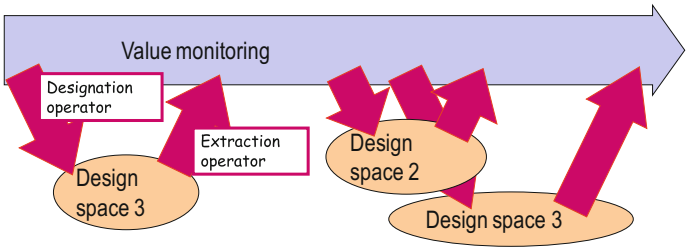


**Fig. 4.13** Design Space and Value Management

initial concept. "A hybrid other than a Prius" might become, for example, "A hybrid with a French touch".

- When knowledge is lacking, the logic of the design space allows it to be created and to be created in a managed way. In contrast, the design space allows a knowledge overflow situation to be managed by arbitrarily limiting the exploration to a small number of K bases.
- When a killer criterion seems inescapable, it is possible to focus the exploration by explicitly rejecting this criterion: "We will do the study first without calculating the costs". For drones: "We will restrict the exploration to drones in simulated flight"; or "we will limit the exploration to a small number of flights in a secure airspace".

As the process gradually progresses, the double expansion occurs not only at the value management level but also at each of the particular design spaces.

**New tools for the creative innovative project:**
These days the designers of tools for creative designers are developing software suites enabling "design workshops" to go from the most exploratory phases to development phases that are not far from rule-based design. For a long time these workshops and software suites have been considered as constrained by the tension between generativeness and robustness: upstream, the possibilities for generation are very open, but explorations are fragile and not robust against standard assessment criteria; downstream, products become robust but the creative possibilities become very limited. Hence we had software suites and workshops which, taking this constraint on board, tended to augment the initial originality so as to better resist the feasibility constraints that would inevitably reduce the initial creativity.

However, recent work (Arrighi et al. 2012) demonstrates software that overcomes the "generativeness-robustness" conflict, simultaneously providing an improvement in robustness and generativeness. Given an initial sketch (let us say a concept state) for a pocket torch in the form of an eye (say), a designer using a standard tool would tend to increase robustness (see below: the object designed from the sketch follows certain constraints on the surface

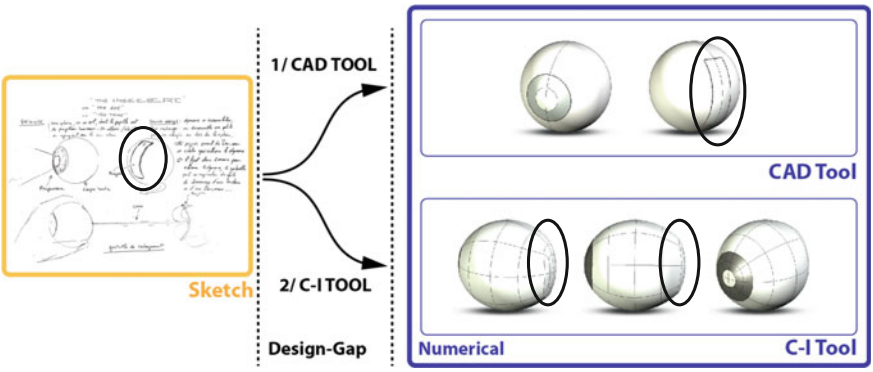


**Fig. 4.14** New tools for the creative designer: a logical process of acquired originality (using this tool the designer can overcome the constraint (acquired robustness) while still being creative in how the constraint is satisfied—whence acquired originality

optical quality, here a sphere); the designer using creative design tools obtains good robustness (better, even: the shapes drawn using the software automatically satisfy a level 2 optical quality) but also achieves greater originality since he is exploring the space of allowable shapes and thus invents a surface that is "more original" than the sketch, but still of level 2 optical quality (namely, a "faceted" sphere"). Hence these software tools can provide a form of "*acquired originality*".

If such tools can be generalized, it becomes possible to envisage design paths richer than the traditional creativity-feasibility compromise (Arrighi et al. 2015) (Fig. 4.14).

### *4.3.2 New Principles of Cohesion: Strategy and Commitment*

In rule-based design, it was possible to study just coordination. In innovative design, cohesion also plays an important role.

In the case of rule-based design, the value and legitimacy of the project were defined at the start. The project's relationship with the company strategy is ensured by agreement on the CQT objective, thus allowing services to be committed to the project. These conditions are not met by the innovative design project (for a detailed discussion of these questions, see (Hooge 2010)). The project organization not only has to manage the coordination (see above) but also the cohesion of the project.

1. *Managing the relationship with strategy:* the strategic nature of exploration evolves over the course of time. Thus Vallourec, a world leader in threaded drill-pipes for oil wells, initiated an exploration of the concept "after the threads have been cut": initially, this was about prudent risk management with not too much in the way of consequences, the expected conclusion being that "after the threads have been cut" was a very long term view; exploration gradually revealed that "after the threads have been cut" was in the dangerously near future—or had the potential for unexpected opportunities. In this case, it was not only the position of the project in the strategic framework that evolved, but the project itself led to a review of the company's strategic line of action. The innovative design project could become the strategy development tool. However, it was the company's underlying logic that was brought into question: this was the *common purpose* so dear to Barnard that could be invoked for the project, whence the management of innovative projects at the highest strategic level in the company, involving all stakeholders.
2. *Managing the commitments*: since the value and character of the innovative project were not well assured, the allocation of resources also became questionable, whence the internal "sponsoring" and the constant necessity for the project manager to secure the commitment of the stakeholders both within and without the project. Note that we are talking about design resources in the broad sense (skills, concepts, etc.) and not necessarily about financial resources. We shall see in Sect. 5.10 that the allocation of financial resources can have counter-intuitive effects (speculative bubble for some technologies) and presupposes particular forms of management.

## 4.4 Conclusion

In innovative design, reasoning follows a double expansion process: expansion of knowledge and new definitions of objects (no longer minimizing the production of new knowledge as in rule-based design). The performance of an exploration project consists of measuring these expansions in accordance with V2OR criteria (and no longer a convergence with respect to some CQT target). The organization rests on managing the learning processes describing the spaces where learning is possible (and often focuses only on certain facets of the concept), taking advantage of local expansions for the gradual structuring of all the alternatives (this is no longer a classic stage-gate where the phases can be predefined). This work demands a constant exchange between design and strategy, and between design and the stakeholders, whose commitment may change over the course of the process and due to the process itself (in contrast with the rule-based design project, whose legitimacy is guaranteed when it is first launched).

In our study of rule-based design, we saw that the success of the "rule-based" project did not rely solely on the management of the project but also, broadly

speaking, on the set of rules on which the project was based. What is the equivalent for the innovative project? The innovative project itself also rests on an innovative design "infrastructure" which ensures the conditions for its success. It is clearly not the rule base itself that plays the most critical role (we have seen on several occasions, as much from the formal as from the managerial point of view, that this rule base is not the most critical element in innovative design): the innovative design infrastructure relies much more on the metabolism of knowledge and concepts, and on the ability to re-use and recycle the expansions produced over the course of time.

### *4.4.1 Main Ideas of the Chapter*

- Concept, and knowledge in C-K theory
- Expansion of the K space, partition of the C space
- Operators (conjunction, disjunction)
- Expansive partition
- Design space, value management

### *4.4.2 Additional Reading*

This chapter can be extended in several directions:

- On the "ecology" of theories of design:
  - see the following theories:

    General Design Theory {Tomiyama and Yoshikawa 1986 #2425; Yoshikawa, 1981 #882
    Axiomatic Design {Suh, 1990 #635; Suh, 2001 #2732},
    Coupled Design Process (Braha and Reich 2003)
    Infused Design, (Shai and Reich 2004a, b)

  - See also models supporting design processes: SAPPhIRE (Chakrabarti et al. 2005), N-Dim (Subrahmanian et al. 1997)
  - See papers comparing theories: ASIT and C-K (Reich et al. 2010); Parameter Analysis & Systematic Design (Kroll 2013); Parameter Analysis and C-K (Kroll et al. 2013);
  - See papers summarizing generativeness and robustness (Hatchuel et al. 2011a):
  - See the special edition of Research in Engineering Design in Design Theory (April 2013). Contributions from (Taura and Nagai 2013; Shai et al. 2013; Le Masson and Weil 2013; Le Masson et al. 2013a; Kazakçi 2013; Hatchuel et al. 2013; Kroll 2013):

- On C-K theory: a few "historical" papers (Hatchuel et al. 2011b; Kazakçi et al. 2010; Hatchuel and Weil, 2003, 2002a, 2009; Kazakçi et al. 2008; Hatchuel and Weil 2007; Kazakçi and Tsoukias 2005; Hatchuel 2005a; Hatchuel et al. 2004):
- "10 years of C-K theory" (Agogué and Kazakçi 2014; Benguigui 2012):
- On applications of C-K theory numerous publications—for an extensive review see (Agogué and Kazakçi 2014; Benguigui 2012); for applications see this and the next chapter.
- On the assessment of innovative projects:
  - on creativity and how to measure it (Csikszentmihalyi 1999; Boden 1999; Weisberg 1992; Torrance 1988; Guilford 1950, 1959):
  - on V2OR and its practice: (Le Masson and Gardey de Soos 2007)
  - on managerial questions associated with assessment: (Elmquist and Le Masson 2009).
- On value management and design space: in management (Hatchuel et al. 2005); Model in engineering design (Hatchuel et al. 2006); examples of such processes: see (Le Masson et al. 2010, Chaps. 11–13) or (Arrighi et al. 2013).

## 4.5 Case Study 4.1: Mg-$CO_2$ Motor

We give below a detailed example of C-K reasoning (see (Shafirovich et al. 2003; Hatchuel et al. 2004)).

### *4.5.1 Before C-K Work*

First of all we give an account of work done before using C-K.

*The reader can try to identify the concepts—sometimes implicit.*

"How to design an Mg-$CO_2$ motor for Mars exploration"? This was the question to which the laboratory for Combustion and Reactive Systems (*Combustion et Systèmes Réactifs*) at CNRS, working notably for ESA (European Space Agency) endeavored to reply at the start of the 2000s.

What was the origin of such a proposal? Let us reconstitute a few elements of the initial knowledge base. While a vehicle engine burns fuel using an oxidant provided by the air (oxygen), a rocket has to carry both fuel and oxidant. For a mission intended to return samples from Mars, the initial mass rapidly becomes considerable: a mission of 500 kg must carry more than 10 tonnes of fuel and oxidant on launch. Several individuals have sought to use an energy source available on Mars, which would mean that the propellant otherwise required for a two-way trip would only have to be sufficient for one way. Given that the Martian atmosphere is 95% $CO_2$, could one use this $CO_2$ as an oxidant? Although the $CO_2$ molecule is quite stable, it can nevertheless support the combustion of metals under particular conditions of temperature and pressure. All that remained was to identify the metal fuel. One of the world's leading combustion specialists, Evgeny Shafirovitch, was working at the CNRS laboratory. Along with other investigators, they showed in the 1990s that it was possible to generate a "specific impulse" using magnesium (Mg) particles in an atmosphere of $CO_2$. Carried from Earth, this result made magnesium a serious candidate for a motor capable of returning the mission to Earth.

*The reader can check that the (implicit) concept "Mg-$CO_2$ motor for a mission to return samples from Mars" is a starting point from which the above reasoning can be reconstituted (check that this concept is consistent with the knowledge available; check that this concept lies at the origin of the new created knowledge).*

Since the first test of the concept was a success, it was tempting to carry out a second, the criterion being the mass landed on Mars. Using Mg-$CO_2$, is the mass landed on Mars less than that which the same mission would require with classical propulsion? Work on this question showed that the answer was negative, and hence the proposal failed the second test. Did they have to give up on this Mg-$CO_2$ motor?

How should the project be relaunched?

*Show that the initial concept should actually be written differently; show that the initial concept "Mg-CO2 motor for a mission to Mars" takes account of all the phases seen above and that it allows design work to be continued.*

One route involved seeking mission scenarios where an Mg-$CO_2$ motor might provide advantages over classical propulsion. All mission scenarios using Mg-$CO_2$ propellant were analyzed systematically. A team was specially entrusted with this work, and each scenario was assessed according to the criterion *mass landed on Mars*. However, the failure was again unambiguous: for all scenarios, Mg-$CO_2$ is not as good as classical propellant.

The story might have ended there, with the research falling victim to the constraints of development or its own inability to better account for these constraints. However, the director of the laboratory, Iskender Gökalp, suggested to one of the students on the design course at the Ecole des Mines in Paris, Mikael Salomon, that he should make use of the C-K formalism to revisit the previous results. This involved seeing whether the design reasoning had been sufficiently rigorous and whether or not it was possible to identify new leads that had remained hidden in the shadows and that might be able to breathe new life into the project. As a result of this work carried out in 2003, an article was published that same year entitled "Mars Rover vs. Mars Hopper" (Shafirovich et al. 2003) demonstrating new avenues for Mg-$CO_2$ combustion in the mission to Mars.

### *4.5.2 C-K Reasoning in the Endeavor*

The rest of the work made use of C-K reasoning in the endeavor.

**A**. First of all, C-K formalism took account of the first stages of reasoning. The initial question was a concept in the theoretical sense since the proposition "an Mg-$CO_2$ motor for Martian exploration" had no logical status but could nonetheless be interpreted in the K base ("motor", "Mg-$CO_2$", "mission to Mars" were known terms). This disconnect was written as a concept in C-space. The two successive partitions linked to research then featured in this space (sufficient thrust, then mission with return of samples or not). The new pieces of knowledge produced by research on that occasion were written under K (see Fig. 4.15).

Let us now examine the research stage of the mission. The concept became "an Mg-$CO_2$ motor for a mission not requiring return of samples"; mission scenarios were generated in K-space. The concept was partitioned with each of the n scenarios generated and scenarios were assessed one after the other (in K). Each scenario ended with a negative conjunction.

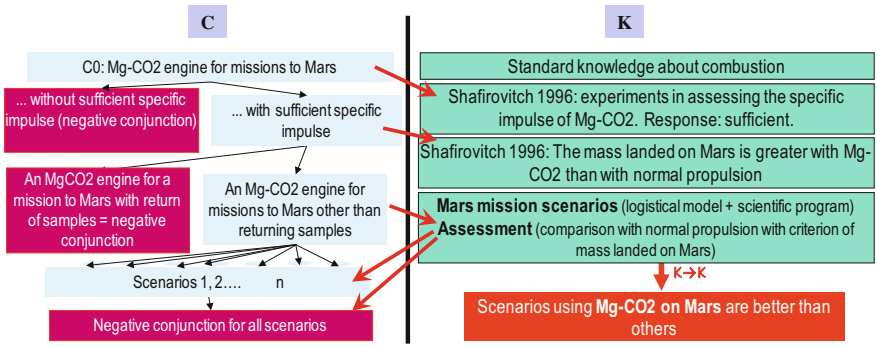


**Fig. 4.15** "research" type and "development" type reasoning

**Guide to interpreting the C-K diagrams** Light gray background: restrictive partitions and existing knowledge.

Dark gray background, light characters: expansive partitions in C and the creation of knowledge in K.

Arrows are operators C ➔ K or K ➔ C or even K ➔ K. They illustrate diagrammatically the main stages of the reasoning

**B**. How to continue? The previous calculations constituted in K an additional knowledge used solely until now for the purposes of assessment. Within the logic of innovative design, this knowledge encouraged the "missions" to be structured differently. In fact, it appeared that these results, even the negative ones, were slightly better if Mg-$CO_2$ were used on Mars. That suggested a new mission partition: the initial concept was partitioned as "used only on Mars" (versus used elsewhere) (see Fig. 4.16). In this case, a new space had to be explored: *that of possible uses of Mg-$CO_2$ technology on Mars*. This partition created the acquisition of knowledge concerning mobility on Mars. The investigation revealed that mobility was not just the operational radius or speed but also susceptibility to unforeseen external conditions (storms, etc.) and the ability to build on scientific opportunities in particular. Hence a partition had to be drawn between *planned mobility* and *unplanned mobility*, and it was thus that the hopper concept emerged. Hence the set of successive expansions allowed *the identity of the object to be profoundly revised*, emphasizing the fact that the assessment criterion was no longer "the mass landed on Mars".

The consequence of this design effort was far from negligible, and there appeared to be real value in using Mg-$CO_2$; the project became financially viable as far as ESA was concerned.

**C**. For all that, "unplanned mobility" remained a concept hard to implement by a research laboratory specializing in combustion, or by the teams developing missions to Mars. The design strategy was therefore to add properties to the initial concept such that *learning in R or in D could be made possible*. Hence it was possible to work on a hopper capable of acting as a substitute for the rover earmarked for the next ESA Mars mission, Exomars 2009. It was known that this hopper should weigh less than 60 kg, complete its mission in less than 180 days,

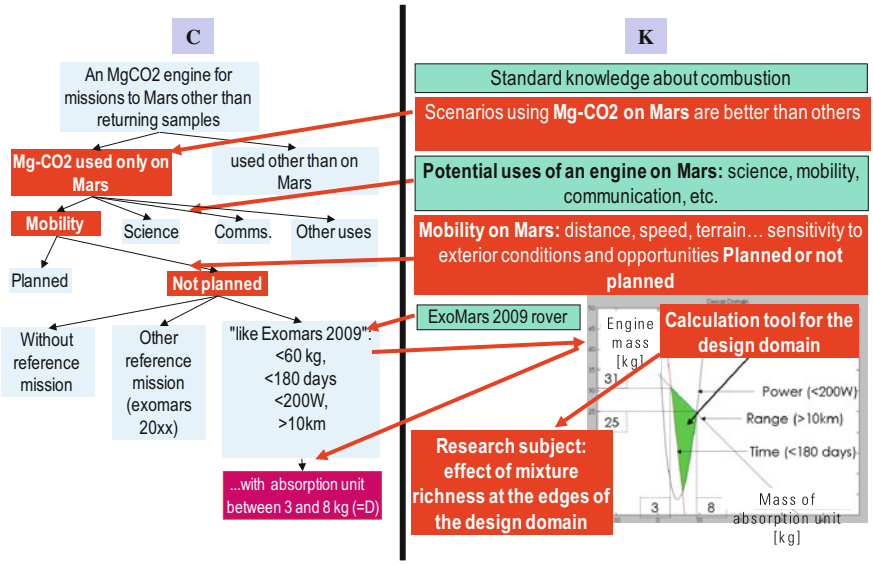


**Fig. 4.16** Revision of the identity of the object. The hopper concept emerges. Reasoning continues until R&D starts

consume less than 200 W (power to be provided by solar panels) and cover at least 10 km. That did not mean that every hopper should meet these constraints; however, the assumption was that working on such a hopper would create valuable understanding for other situations.

Given the constraints of the rocket equations and an understanding of the technology of $CO_2$ absorption, these new objectives immediately put fairly precise dimensional restrictions on the absorption unit and the mass of the Mg-$CO_2$ motor, these constituting their "design domain". R and D could work on this design domain: D would develop a motor whose mass would correspond with the constraints of the "specifications sheet"; R would concentrate on the effects of modifying the combustion parameters (mixture richness, for example) at the boundaries of the domain.

The reader may check this example for V2OR assessment criteria. We give a few pointers:

*Variety*: the Mg-$CO_2$ system satisfied the variety criterion for the proposed avenues.

*Originality*: the hopper concept (vs. rover) or that of the unplanned mission (vs. scenario) were revisions of certain definitions.

*Value:* it is of interest to observe that the expansive partition of the missions gradually led to a profound transformation of the value criteria: no longer was the criterion that of the mass landed on Mars, but flexibility. An understanding of the mobility conditions on Mars were also sources of value.

*Robustness:* the work gradually identified a design domain for the motor and questions that R&D could tackle. Other criteria included data on the $CO_2$ absorption units, an understanding of the combustion of non-optimal mixtures, etc.

## Frido SMULDERS

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Research interests:
Trans-disciplinary and collaborative design & innovation
Entrepreneurial behavior related to (disruptive) innovation
The fundamental role of design and its symbiotic partner engineering

**Title of the Presentation:**

The Dreamliner's bumpy road to takeoff. Overlooked Design & Innovation Theory as root cause?

**Synopsis:**
The 787 Dreamliner was announced in January 2003 and delivered to its first client, All Nippon Airways, in September 2011. The delivery of the first plane however, was scheduled a good 40 months earlier, April 2008. This delay almost took Boeing into bankruptcy because the development costs during those 40 months believed to have quadrupled from 6 bilj $ to 27 bilj $. The original deevlopment schedule from announcement till first delivery was about 63 months. They needed an extra 40 months to get the fisrt plane deliverd. So, one could hypothise, that Boeing basically redesigned the two thirds of the whole plane.
What went wrong here? Using the case of Boeing's Dreamliner, this session aims to connect theory to practice and vice versa answering the question: Based on the design & innovation literature until the early 2000's, could Boeing have known that the way they structured and organized the 787 development programme was not going to work? Where there any warnings and or precautions taken?
We will discuss possible answers to these questions in the light of the literature until the early 2000's. As a second step we will look from the perspective of recent design & innovation literature and see if 20 years later the upcoming problems were obvious.
As a related topic we will discus the role of design in relation to the recent problems of Boeing's 737 Max. Grounded for almost 24 months, and again bringing Boeing towards the edge of bankruptcy. What are the similarities between these two corporate disasters?
Finally, and that moves to you as a reseacher, we'll discuss your responsibilities as academics regarding the theory-practice chasm.

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*Global Strategy Journal*
*Global Strat. J.*, **3**: 41–66 (2013)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1111/j.2042-5805.2012.01050.x

# MANAGING A GLOBAL PARTNERSHIP MODEL: LESSONS FROM THE BOEING 787 'DREAMLINER' PROGRAM

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*Little research has examined the integration challenges in globally disaggregated value chains in a complex NPD effort or the tools managers use to overcome such challenges. Drawing on Boeing's 787 program, we highlight integration challenges Boeing faced and how it addressed them through recourse to partial co-location, establishing a centralized integration support center, reintegrating some activities performed by suppliers, and using its bargaining power to facilitate changes. The integration tools Boeing employed were geared toward two primary objectives: (1) gaining increased visibility of actions and visibility of knowledge networks across partner firms; and (2) motivating partners to take actions to improve visibility. These findings add empirical traction to the theoretical debate around the integration tools and the role of authority in the knowledge-based view of the firm. Copyright © 2013 Strategic Management Society.*

## INTRODUCTION

How do firms integrate knowledge in a globally distributed new product development (NPD) effort involving cutting-edge technology? Addressing this question is important because value chains in numerous industries have become increasingly globally disaggregated (Mudambi and Venzin, 2010). Also, firms are locating NPD and R&D activity in offshore locations to leverage knowledge and talent (Lewin, Massini, and Peeters, 2009; Thursby and Thursby, 2006). Such trends have increased the importance of integrating globally sourced external knowledge with internal firm knowledge and capabilities.

The importance of integrating is especially true for firms engaged in strategic NPD activities that often rely on external sources such as suppliers and customers for specialized knowledge. With increasing complexity, rapid technological advance, and widely dispersed knowledge and expertise, it is difficult for any single firm to internally assemble the knowledge needed for complex NPD projects. Instead, firms must depend on external innovation partners to build products within acceptable budgets, timelines, and financial risk (Chesbrough, 2003; Madhok, 1997; Powell, Koput, and Smith-Doerr, 1996). Typically, in order to develop high value products or services, firms must acquire external knowledge and effectively integrate it with internal knowledge (Becker and Zirpoli, 2011; Dyer and Hatch, 2006; Wadhwa and Kotha, 2006).

Past research has shown that integrating knowledge across geographies can be difficult (Bartlett and Ghosal, 1989; Meyer, Mudambi, and Narula, 2011; Mudambi, 2011), especially from foreign suppliers and alliance partners (Almeida, Song, and Grant, 2002). This is because tools such as normative integration, social integration, and authority

Keywords: global integration; qualitative study; activity and knowledge visibility; knowledge-based view of the firm; disaggregated value chains
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relationships (Bartlett and Ghosal, 1989; Martinez and Jarillo, 1989; Rugman and Verbeke, 2009) used by the multinational enterprise (MNE) to integrate activities across geographies are unavailable in *globally disaggregated* buyer-supplier supply chains (Rugman, Verbeke, and Nguyen, 2011).[1] Although (partial) co-location or significant travel across the globe is theoretically feasible, it is prohibitively expensive in practice, forcing firms to consider alternatives. As well, the need for specialized external sources of knowledge may require a buyer to work with suppliers with the requisite knowledge but no prior relationship.

Understanding how to effectively integrate knowledge among the subsidiaries of an MNE is one of the most important research areas in global strategy (Kogut and Zander, 1993; Mudambi, 2011). However, little research has examined the integration challenges in *globally disaggregated value chains* in a complex NPD effort involving cutting-edge technologies or the tools used by managers to overcome these challenges. This study attempts to address this gap by exploring the question of *how a firm integrates globally disaggregated new product development and manufacturing*. To address this, we identify the components, tools, and mechanisms that underlie global integration capability.

Since the research question addresses issues pertaining to a globally disaggregated complex NPD initiative, we chose a setting in which such processes are still unfolding. To this end, we examine Boeing's 787 *Dreamliner* program. The 787 airplane is a breakthrough product involving cutting-edge technologies, which required a significant integration effort between suppliers and Boeing locations across the globe. The 787 airplane represents a breakthrough product because it is the first passenger plane built using composite materials, which pushed the technological frontier in terms of flying a certain distance with 20 percent less fuel than comparable planes.

We undertook a qualitative study of this globally distributed, complex NPD project because the introduction of a new airplane provided the ideal context for examining issues in global supplier integration. We explore the different types of integration challenges faced by Boeing in the 787 program, and observe how these issues were resolved in order to uncover the building blocks of a global integration capability. Integration in this context takes place in an unstructured setting laden with ambiguity, which makes it difficult to specify interdependencies across firms and geographic boundaries *a priori*. In addition to the role played by traditional mechanisms that drive integration, the chosen context allows for other potentially interesting mechanisms to be identified and discussed. This is best accomplished using a qualitative approach (Eisenhardt and Graebner, 2007).

Our findings suggest that Boeing encountered three kinds of integration problems in implementing the 787 airplane program. It achieved integration through recourse to partial co-location, established a unique IT-enabled centralized integration support center, reintegrated some activities previously performed by suppliers, and used its bargaining power to facilitate integration. We found that the integration tools employed were geared toward two primary objectives: (1) gaining increased visibility of actions and visibility of knowledge networks across partner firms; and (2) motivating partners to take actions that would improve visibility. These findings contribute to our understanding of the components of a global integration capability and add a level of empirical traction to the largely theoretical debate around the role of authority in the knowledge-based view of the firm.

## Background literature

An extensive amount of international business research has considered the difficulty in integrating knowledge across locations *within* an MNE (e.g., Mudambi, 2011; Rugman and Verbeke, 2009). In contrast, we focus specifically on knowledge integration *across* geographically distributed buyers and suppliers involved with complex NPD programs in a global setting. In general, integrating knowledge-intensive activities between firms is more difficult than within a single firm because personnel from different firms lack a: (1) common language, common culture, or agreed upon decision principles that arise naturally within firms (Grant, 1996; Kogut and Zander, 1992, 1996); and (2) unified source of authority to enforce decisions or break deadlocks that arise from conflicts (Williamson, 1985).

Prior work suggests that buyer-supplier relationships achieve knowledge integration by broadly relying on three sets of tools: (1) co-locating buyer

[1] Normative integration provides benefits such as a common language and agreed upon decision rules (Ghoshal and Nohria, 1989), whereas social integration enables the transfer of sticky knowledge through strong ties (Frost and Zhou, 2005; Hansen, 1999, 2002).



DOI: 10.1111/j.2042-5805.2012.01050.x

and supplier engineers (Dyer, 1997; Dyer and Nobeoka, 2000; Helper, MacDuffie, and Sabel, 2000); (2) leveraging relationship-specific assets (RSA) developed in prior interactions (Dyer and Singh, 1998; Kale and Singh, 2007); and (3) using modular product architectures (Baldwin and Clark, 2000). Such tools have significant shortcomings when integrating knowledge in buyer-supplier NPD relationships that are *globally* distributed, as will be explained below.

### *Co-location and integration*

One approach to integrating knowledge between buyer and supplier engineers is through co-location, at least for the critical phases of a project (Dyer, 2000; Lincoln and Ahmadjian, 2001; Olson and Olson, 2000). Dyer and Nobeoka (2000) have shown that geographic proximity is a key consideration in creating supplier groups in the Toyota network. Typically, Toyota has engineers from its suppliers working in its facilities for extended periods, and vice versa, leading to human capital co-specialization (Dyer, 1996; Dyer and Nobeoka, 2000). Operating within the same environment facilitates the emergence of shared contextual knowledge, which in turn, promotes integration (Kraut *et al*., 2002; Olson *et al*., 2002).[2] Helper *et al*. (2000) argue that co-location supports monitoring and promotes socialization between buyer and supplier employees, leading to superior integration outcomes. In short, co-location facilitates effective integration.

However, in globally distributed NPD projects, (partial) co-locating supplier engineers and/or facilitating extensive travel across the supplier network is prohibitively expensive in practice, leading firms to look for alternatives to achieve integration. Also, in globally disaggregated projects, differences in language, culture, and institutional diversity further exacerbate the coordination problems that arise due to geographic distance such as the lack of frequent, rich situated interactions between interdependent agents.[3] It is important to note that whereas prior work has pointed out the problems arising from geographic dispersion, it is still an open question as to how such relationships should be managed to achieve effective integration between the assembler and suppliers when co-location is constrained.

### *RSA and integration*

Research suggests that when exchange partners develop RSA, or relational capital, they are more effective in integrating activities (Doz, 1996; Dyer and Singh, 1998; Kotabe, Martin, and Domoto, 2003). Relationship duration influences the stock of RSA between partners, with the current project benefitting from learning in prior interactions. As partner-specific experience and learning accumulate, they create RSA such as the development of a common language, interaction routines, and a better understanding of partner decision-making procedures, leading to better knowledge exchange and superior integration (Dyer and Singh, 1998; Gulati, Lavie, and Singh, 2009). RSA among established partners could include aids in achieving integration in NPD, such as boundary objects that can convey meaning across different functional specialists (Carlile, 2002) and the presence of boundary spanners with the recognition and credibility across the different units (Mudambi, 2011).

In globally distributed NPD projects involving cutting-edge technologies, RSA may be unavailable or severely constrained. First, the necessary technological know-how may be available only through firms that share no prior relationship (Garud and Munir, 2008). For instance, when electronics technology was incorporated into cars, automotive manufacturers were forced to seek *new* partners with such expertise (Lee and Berente, 2012). Second, with a prior partner, a qualitative change in the nature of the relationship could limit the usefulness of accumulated RSA in achieving integration outcomes. For example, aids in integration (such as boundary objects) may need to be renegotiated across the different experts involved and new boundary spanners with credibility across the new functions identified. Thus, when U.S. automakers adopted Japanese supply management practices (e.g., JIT and Kanban) and outsourced complete subsystems, both manufacturers and suppliers had to learn how to manage this transformation to their partnership.

[2] Dyer (2000) shows that the average distance between Toyota's and its supplier plants is much less than the corresponding distance for GM and argues that such close physical proximity provides Toyota with an advantage in integrating supplier activities relative to GM, for it enables rich and fast communications.
[3] While it may appear that the challenges faced by a firm in managing a disaggregated supply chain in general is not different from that of managing a *globally* disaggregated supply chain, the differences lie primarily in the degree to which such integration is different.



DOI: 10.1111/j.2042-5805.2012.01050.x

*Modularity and integration*

Another important approach to integrating supplier knowledge is a reliance on modular product and organization architectures. Organizational architecture represents the division of labor between the firm and its suppliers and the integration mechanisms used to coordinate activities (Baldwin and Clark, 2000), whereas product architecture represents a product's deconstruction into subcomponents and their interactions (Ulrich and Eppinger, 2005). Research has shown that when a product's architecture and its underlying knowledge are modular, integrating knowledge from external sources is less difficult (Baldwin and Clark, 2000; Brusoni, Prencipe, and Pavitt, 2001).

Entirely modular product architectures are relatively rare; this is especially the case with complex NPD projects involving cutting-edge technologies, due to the significant uncertainty regarding the nature of interdependence between the subcomponents (Ethiraj and Levinthal, 2004). In such situations, product designers often learn about component interdependences via trial and experimentation (Garud and Munir, 2008). In new automotive design, for example, designers cannot predict *ex ante* how components will interact to generate system performance such as noise or vibration (Becker and Zirpoli, 2009), a factor that constrains the designer from realizing a modular organizational architecture. In such settings, firms may be better off using an *integral* rather than a *modular* perspective (Siggelkow and Levinthal, 2003). Thus, NPD efforts involving integral products and breakthrough innovations require significant cross-team integration across different components (Sosa, Eppinger and Rowles, 2004; Zirpoli and Becker, 2011). Since suppliers often hold critical knowledge about subsystem designs, effective buyer and supplier knowledge integration is critical for breakthrough NPD projects.

In sum, NPD programs involving cutting-edge technologies that are distributed across *both* geographic and firm boundaries present unique integration challenges. As shown in Table 1, integration tools designed to manage such programs are limited. Co-location can be prohibitively expensive and technological uncertainty precludes modularity as an effective integration strategy. The need for specialized knowledge may require firms to work with partners who have no prior RSA, while changes to the program task requirements can make RSA from prior projects less effective. Finally, the unique integration tools available to an MNE are not available across buyers and suppliers. This suggests a research gap in our understanding of how firms effectively integrate activities in *globally disaggregated* complex NPD projects, a gap this article attempts to address.

## METHODS

### Approach and context

Our approach represents a combination of theory generation (Eisenhardt, 1989) and theory elaboration (Lee, 1999). We drew upon the emerging findings to elaborate and sharpen assertions made in these literatures. To guide the inquiry, we employed a conceptual framework consisting of a broadly defined

Table 1. Integration tools available in globally disaggregated NPD projects

| Integration tools | Available within firm boundaries | Available across firm boundaries | Available in a globally disaggregated NPD program? |
|---|---|---|---|
| Authority | Yes | No | No |
| Normative integration | Yes | No | No |
| Relationship-specific assets | Yes | Yes | Only with partners with prior relationships* |
| Social integration | Yes | Yes | Only with partners with prior relationships |
| Modular architectures | Yes | Yes | Difficult to achieve in an NPD program that uses cutting-edge technology and a new approach, regardless of whether the activities are organized within or across firms. |

*Relationship-specific assets (RSA) include things such as shared knowledge of decision-making procedures, development of a common language, and using shared routines and processes (Dyer and Singh, 1998). The purpose of normative integration is essentially to develop these same integration tools across subsidiaries of an MNE (Ghoshal and Nohria, 1989).



DOI: 10.1111/j.2042-5805.2012.01050.x

research question (provided in the introduction) and some potentially important constructs (e.g., modularity, co-location, RSA) from the extant literature.

*Choice of Boeing and 787 program*

Our choice of Boeing was driven by theoretical and pragmatic reasons. On the theoretical front, we focused on a program that represents a globally distributed NPD effort involving cutting-edge technologies where integration between the assembler and suppliers is crucial to program success. Additionally, the program was subject to a number of delays, chiefly attributed to integration issues between Boeing and its partners. Understanding the causes for these delays and the subsequent actions and outcomes provides a unique quasi-experimental setting to observe the development of integration capabilities in the context of a global NPD project.[4] More pragmatically, the access to significant personnel involved in the program provided a unique opportunity to observe the development of a complex product and its impact on Boeing's attempt at global integration.

The use of Boeing's 787 program represents a single case, but it was chosen deliberately due to the insights it could offer. Boeing's introduction of the 787, the real-time setting for the study, represents a revelatory case (Yin, 1994) and, as such, represents an important setting in which to study the research questions of interest. To industry observers, the Boeing 787 airplane represents a breakthrough product because 'with this airplane, Boeing has radically altered—indeed revolutionized—its approach to designing, building, and financing new products. Its role is that of 'systems integrator,' coordinating the design and development efforts of a group of largely non-U.S. partners' (Newhouse, 2007: 27).

*The chosen time frame*

Since the factors influencing the development of organizational capabilities and organizational design often include path dependencies that are cumulative and historically conditioned (Garud and Kotha, 1994; Langlois, 1988), a research design that generalizes uniqueness needs to be longitudinal. We selected 1996 as the starting point for analysis, since this was the year when Phil Condit unveiled Boeing's Vision 2016, the document setting forth the company's strategy for the next 20 years. Our end point was September 2011, the month that Boeing delivered the first aircraft for commercial use.

## Data sources

We employed data from three sources: (1) interviews with Boeing senior executives, its suppliers, and industry experts; (2) press releases, internal Boeing publications, and other information available from public sources; and (3) e-mails and phone calls with executives to fill in gaps.

*Interview data*

Our primary sources were interviews conducted with multiple respondents within Boeing and its suppliers. We began the study with one of the authors conducting a four-hour interview with Phil Condit, former Boeing CEO, on whose watch the 787 was conceptualized and launched. This was followed by two separate interviews with Mike Bair, the first 787 program manager. We interviewed others, including the vice presidents in charge of supply chain management and quality; the director responsible for marketing and sales; and the airplane's interior design team; and other senior executives from units across the company. We also specifically interviewed three separate managers responsible for the Production Integration Center, one of the important tools Boeing employed to get greater control of its production system (described in detail later), to access *non-confidential* information about how this center functioned.

On two different occasions, we spoke to one of the directors in charge of the Vought factory in Charleston, South Carolina (one of Boeing's major suppliers, prior to the acquisition of this factory by Boeing). We did follow-up phone calls and e-mails to fill in the gaps after Boeing's acquisition of the Vought factory. Over a four-year period, we interviewed more than 20 senior executives directly related to the program. All interviews were recorded and professionally transcribed verbatim. Each interview lasted 1.5 hours on average and resulted in transcripts averaging 30-plus pages.

All interviews consisted of open- and close-ended questions. The closed-end part asked the senior manager to provide background information on the

[4] For this study, we specifically concentrate on the integration issues between Boeing and its six major structural partners: three Japanese firms, Mitsubishi, Fuji and Kawasaki; an Italian firm, Alenia Aermacchi; and two U.S. firms, Vought Aircraft Industries and Spirit Aerosystems.



DOI: 10.1111/j.2042-5805.2012.01050.x

program so we could supplement publicly available information with information directly gleaned from executives within Boeing. The open-ended part focused on non-confidential information unreported in the public media and Boeing press releases. Where appropriate and when relevant, we solicited information on managerial intentions and interpretation of how the program was conceptualized, structured, and unfolded over time. We used both nondirective and directive questions at different points in the interview to ensure data accuracy while reducing the priming effects where informants feel the need to answer a question in a specific way (Bingham and Haleblian, 2012).[5]

*Books, cases, trade reports, and newspaper articles*

We supplemented interviews with secondary sources, including accounts provided by books (Newhouse, 1985, 2007; Norris *et al*., 2005), business cases (Kotha and Nolan, 2005; Esty and Kane, 2001), magazine and newspaper articles, investment and industry reports, and Boeing press releases. We also examined media reports, which often provide contextual information about industry dynamics and firm- and program-level actions and activities. Investment and industry reports (e.g., Reuters, Flight International) enabled us to validate emergent ideas regarding changes observed over time. Additionally, we examined more than 800 newspaper and magazine articles on the program. Such multiple sources allowed us to examine the data from many vantage points and triangulate interview data with publicly accessible data such as media reports, press releases, and industry reports (Yin, 1994).

### Analysis

We first analyzed the data by building our own case history for the Dreamliner 787 program. This case history was circulated to Boeing executives and corrected for factual errors. Using the material collected, we documented the airplane's evolution chronologically and then systematically examined the 787 program as it unfolded over time. To enhance theoretical sensitivity, we also systematically compared integration tools used across different partners over time. We were sensitive to the characterization of major structural partners to categories identified from public sources such as the extent of co-location and prior relationships with the Boeing program. Typical of qualitative research (Brown and Eisenhardt, 1997), we checked the validity of our insights with colleagues and senior executives. This iterative process resulted in multiple revisions and refinements. In the sections that follow, we discuss our detailed understanding of how the 787's organizational architecture and Boeing's integration capabilities evolved over the time period being studied.

## THE BOEING 787 PROGRAM: A GLOBALLY DISTRIBUTED DESIGN AND PRODUCTION SYSTEM

### Background and antecedents

In 1996, Phil Condit, the newly appointed Boeing CEO, unveiled a vision for the company. Dubbed the *Boeing 2016 Vision*, it presented the company manifesto: 'People working together as a global enterprise for aerospace leadership' (The Boeing Company, press release, 1998). In addition to becoming a global enterprise, Condit identified three major competencies that Boeing would leverage, *large-scale systems integration* being one. To industry observers, this meant Boeing wanted to transform its identity from a wrench-turning manufacturer into a master planner, marketer, and snap-together assembler of high tech airplanes (Newhouse, 2007).

Four years later, after two false starts, Boeing announced the 787 airplane (The Boeing Company, press release, 2002), a super-efficient plane that could fly as fast as today's fastest commercial airplanes, a major breakthrough for the aviation industry (Kotha and Nolan, 2005). A few years prior, in 2000, Airbus announced the commercial launch of the A380 super-jumbo, and by 2003 Airbus succeeded Boeing as the world's largest builder of commercial airplanes for the first time (Taylor, 2003). As a result, industry observers questioned Boeing's commitment to the commercial aviation industry as well as its ability to compete effectively against Airbus (cf. MacPherson and Pritchard, 2003). Given such concerns, the flawless execution of the 787 program was a competitive necessity for Boeing.

### Organization architecture of the 787 program

Boeing decided to build the 787 airplane using titanium and graphite (Norris *et al*., 2005) making it the

[5] The information presented here includes only publicly disclosed details and contains no confidential information about the program.



DOI: 10.1111/j.2042-5805.2012.01050.x

world's first commercial aircraft built with composite materials, a decision that would have profound implications for the design and manufacture of the aircraft. The design called for decomposing the airplane's fuselage into major structural sections that could be built independently and mated together at the final assembly factory.

*The global partnership model*

Boeing decided this innovative product design was better suited to a *global partnership model* than earlier airplanes; now a global team of risk-sharing partners would help finance, develop, and market the airplane and Boeing, as the lead integrator, paid partners only after the airplanes were delivered to customers (*Seattle Times*, 2003). Boeing reasoned that risk-sharing partners would have an incentive to complete the work efficiently and help sell the airplane in their respective markets.

*Transformation of supplier relationships*

The 787 program represented an entirely new way of working with partners. In the past, Boeing had worked with its partners in a mode called *build to print* where engineers developed the design and detailed drawings (often hundreds of pages) for every part of the plane and then contracted with partners to build the parts to exact specifications. In the 787 program, Boeing requested each partner to *build to performance*, where Boeing engineers provided specifications comprising tens of pages with performance metrics that the parts needed to meet (Kotha and Nolan, 2005). Innovation, detailed drawings, and tooling would become the direct responsibility of the partners. Bair, the first 787 program leader, elaborates:

> 'What we had done (was take) the way that we have historically dealt with system suppliers and moved that into the airframe of the airplane. So rather than us doing all the engineering on the airframe and having suppliers do build-to-print, we put a fair amount of airplane design detail into the supply base. *The fundamental premise there is that you want to have the 'design and build' aspects aligned because to think that you could optimize for efficient production in someone else's factory, we have proven over and over again, is not the right answer. The suppliers know their factory and their capabilities*. They need to know this is going to work in order to make the subtle design decisions that they make in order to ensure that they optimize the production of the airplane.' (Mike Bair, pers. comm., 2008)

Figure 1, Boeing's template for implementing its global partnership strategy, illustrates how the airplane's major sections would be decomposed and built by partner firms. In all, 15 Tier 1 partners formed Boeing's new global network, with six taking on the responsibility for large structural sections (*Seattle Times*, 2003).

Bair noted that access to IP, as well as the need to reduce market risk, drove Boeing's supplier selection strategy:

> '[We looked] outside of the United States for partners. *The thing that we were after was intellectual capital*. We cast a net fairly wide in terms of getting the right, and the smartest, people in the world to help design this airplane. For example, the Italians, who were building part of the body and the horizontal tail, had some unique IP that we didn't have. The Japanese have brought us certain measured discipline. It is sort of foreign—certainly foreign to the United States and really foreign to the Italians. We really have gotten the best of the best in terms of getting these kinds of benefits.' (Mike Bair, pers. comm., 2008)

Another new element in this approach was the requirement that suppliers assemble subcomponents or *stuff* the modules before these were shipped to Boeing for final assembly. In previous programs, Boeing had assumed these tasks. Condit clarified the approach:

> 'It isn't that a lot of things are 'totally' new. Often it is simply that we haven't done it exactly this way in the past. What is 'new' is we are going to have a global partner 'stuff' the fuselage components, and we are going to snap it together with the central wing mount in an extraordinarily short time period.' (Phil Condit, pers. comm., 2008)

In other words, the 787 would be decomposed into completed *integrated assemblies*, or work packages, to be built around the globe and then transported to a Boeing final assembly plant at Everett, Washington.

Boeing chose an air transportation system to speed up delivery of work packages to Everett. The expected delivery time for work packages would be a day, rather than as much as 30 days in other airplane programs. During final assembly, the large integrated assemblies would be snap-fitted together in three days. The approach minimized the slack



DOI: 10.1111/j.2042-5805.2012.01050.x

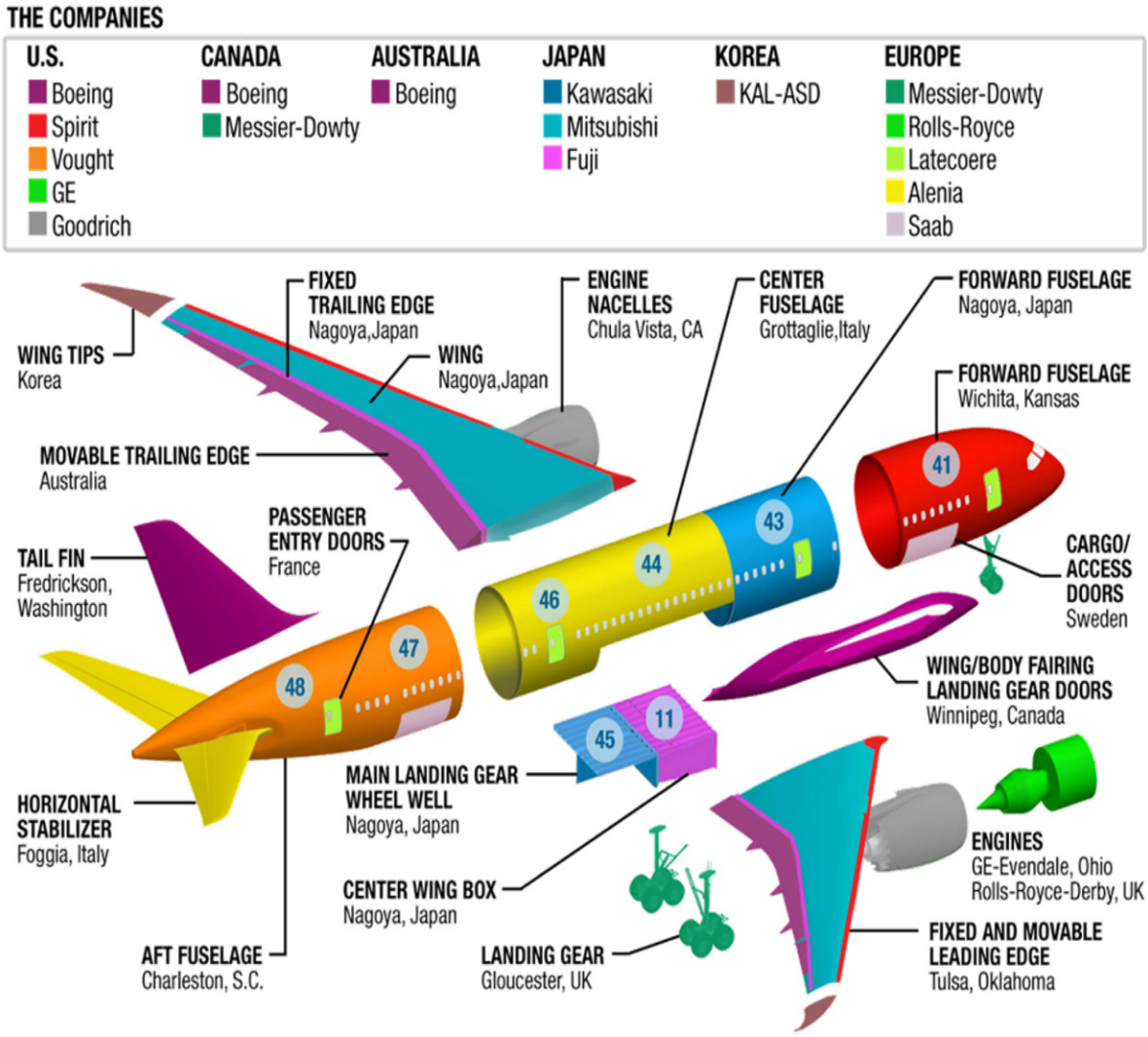


Figure 1. List of Boeing's global supplier partners for the 787 airplane
Source: Kotha and Nolan, 2005

available in the system and required a tight integration between Boeing and structural partners.

*Organizational architecture*

In the 787 program, Boeing had radically redesigned both the product and organizational architectures compared to programs such as the 767 or 777. The 787's organizational architecture is shown in Figure 2 (as finalized in 2004); the dotted line section represents Boeing's boundaries (the Everett factories), distinguishing it as a separate entity. The small *e* in the figure denotes the diminished engineering role of Boeing's engineering (relative to past programs), since partners handled many aspects of the airplane's design. The circled *E* in the various supplier boxes denotes the engineering/design work passed on to partners. The engineering and manufacturing interactions (shown by the arrows) at partner sites represent the 'design and build' alignment required for efficient production. Figures 1 and 2 together illustrate the 787's organizational architecture under which two factories—the Global Aeronautica (henceforth GA—a joint venture between Alenia and Vought) and Vought factories in Charleston—were central to the smooth functioning of the system because it was here that the partners preassembled major structural sections.



DOI: 10.1111/j.2042-5805.2012.01050.x

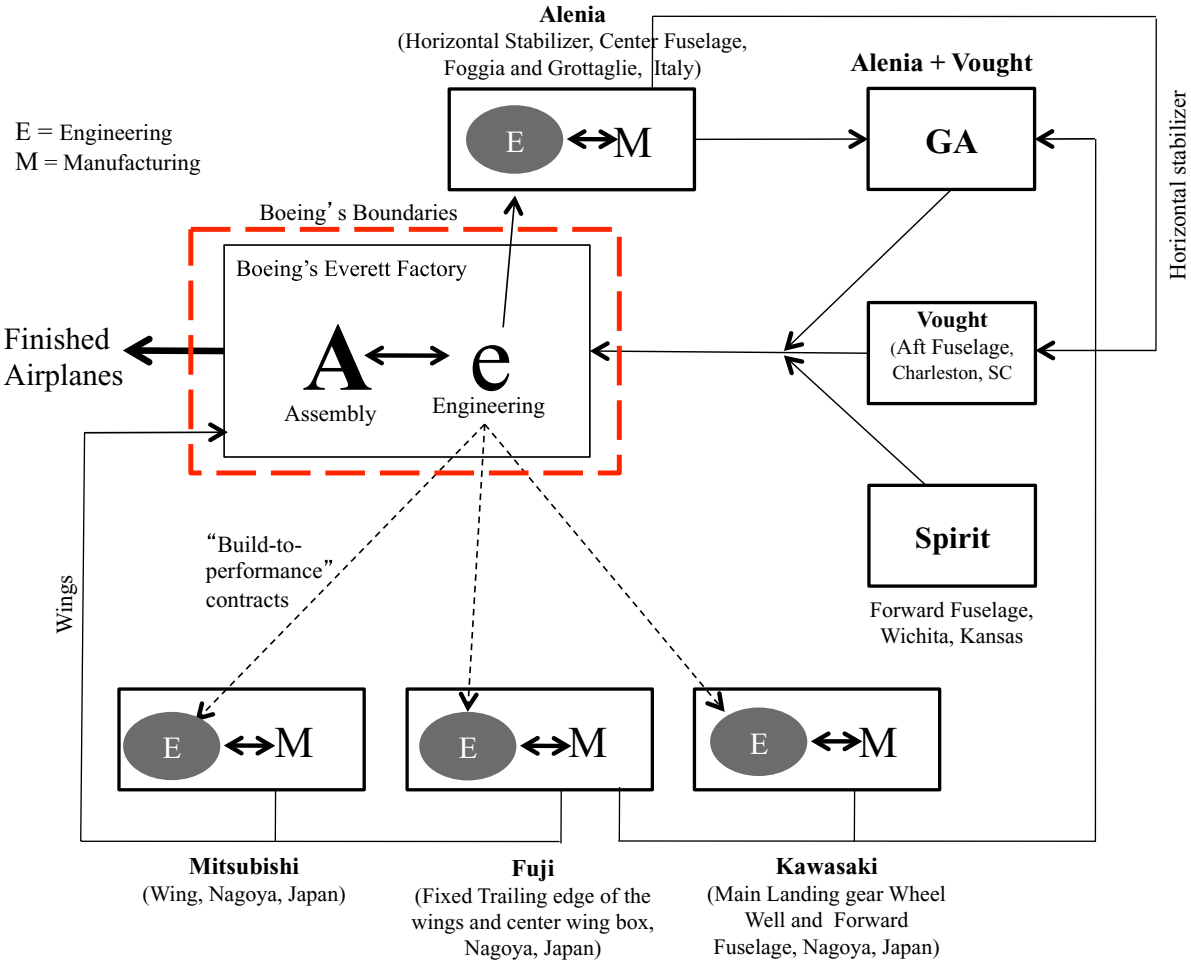


Figure 2. Simplified view of early architectural design for the 787 airplane, 2004
Source: Author's representation of Boeing's approach

In 2004, Boeing began taking customer orders and expected to deliver the airplane in four years. Customers eagerly signed on, making the 787 the fastest-selling airplane in commercial aviation history. However, events turned out differently than planned during implementation.

## Delays to the 787 program: integration problems and attempts to fix them

Starting in September 2007, the program started running into embarrassing delays—delays that represented a serious setback for Boeing's intent of being a *large-scale systems integrator*. Table 2 provides a summary and reasons for the 787 delivery delays. The delays were attributed to Boeing's problems in implementing the global partnership model. According to *The Wall Street Journal* (Lunsford, 2008b: B1):

> 'Boeing extolled the business virtues of having suppliers from as far away as Japan and Italy build much of the fuel-efficient new jetliner, with Boeing performing final assembly . . . But the plan backfired when suppliers fell behind in getting their jobs done . . . [and] Boeing was forced to turn to its own union workforce to piece together the first few airplanes after they arrived at the company's factory in Everett with thousands of missing parts.'

Jim McNerney, Boeing's current CEO readily admitted Boeing's difficulty in executing its chosen strategy and noted:

> 'But we may have gone a little too far, too fast in a couple of areas. I expect we'll modify our approach somewhat on future programs—possibly drawing the lines differently in places with regard to what we ask our partners to do, but also sharpening our tools for



DOI: 10.1111/j.2042-5805.2012.01050.x

Table 2. Major delays announced to the 787 program and stated reasons (2007–09)

| Delay # | Delay announcements | Cumulative delays | Reasons for the delays as reported by Boeing and discussed in the media |
|---|---|---|---|
| **1** | September 2007 | 3 months | Problems are the result of unexpected shortages of fasteners and the inability of Spirit to deliver the forward fuselage module (see Section 41 in Figure 1). Spirit ascribed the delays to difficulties in completing the software code needed for flight control systems by Honeywell, a Tier 2 supplier to Spirit. |
| **2** | October 2007 | 6 months | Media reports and Boeing blamed the problems on Boeing's **supply chain network.** No details were specified. |
| **3** | January 2008 | 9 months | Boeing blames the delay on start-up challenges it faced in Boeing's factory and in factories of the extended global supply chain. The focus of blame is on **supply chain and capabilities** of the Boeing subsidiaries and its Tier 1 partners. |
| **4** | April 2008 | 1 year | Boeing blames the delays on problems with **carbon fiber technology** in the center wing box made by one of its **Japanese partners**. The media identified this partner as Kawasaki Heavy Industries (KHI). The wing-box was too light and needed strengthening. Although this was the primary responsibility of KHI, Boeing engineers worked on a patch to fix the early airplanes with this problem.<br>Boeing blames **botched assemblies of the first fuselages** at the Charleston, Vought, and GA factories for most of the delays. Incomplete work transported from these factories to Boeing's plant at Everett played a large part in the issues faced by the final assembly line at the Everett factory. Vought, in turn, blamed Kawasaki Heavy Industries for sending incomplete work and noted that they (Vought) lacked authority to discipline this supplier. |
| **5** | December 2008 | 2 years | Delays were due to **improper work done by partners**. Boeing had to replace improperly installed fasteners in the early production airplanes. The media attributed the improper fastener installation to poorly written technical specifications that Boeing provided its partners as well as suppliers′ lack of experience with this kind of work (suppliers, in this case, were GA and Vought).<br>Boeing is faced with a 58-day strike by the machinists' union at its final assemble plant at Everett. Machinists are unhappy with wage increases offered by Boeing and they are also **unhappy with Boeing's 'global partnership model**,' where 787 jobs were being outsourced. |
| **6** | June 23, 2009 | 2+ years | Delays are blamed on **structural flaws** resulting from mating the wings to the fuselage of the airplane. The flaws are blamed on engineering issues, but no mention of who is responsible for the flaws. Mitsubishi Heavy Industries, a Japanese partner, was responsible for the wings. |

> overseeing overall supply chain activities.' (The Boeing Company, press release, 2008)

This quote indicates that Boeing had limited integration capabilities and many of the partners lacked the required skills too. To fix the problems, McNerney directed that 'Boeing managers take a more aggressive role in sticking their noses into suppliers′ operations, including stationing Boeing employees in every major supplier's factory' (Lunsford, 2008a: B1). He named Pat Shanahan to head the program and reassigned Bair.



DOI: 10.1111/j.2042-5805.2012.01050.x

As Table 2 illustrates, the botched assembly of the first 787 fuselages at two factories in Charleston were responsible for the early delays. At Charleston, Vought Aircraft Industries managed one factory and GA managed the other. Incomplete work from here 'played a large part in the snafus that snarled the final assembly line in Everett that has delayed the 787's first flight by 14 months' (Gates, 2008: A1). In response, Elmer Doty, CEO of Vought, countered:

> 'Vought's role in the venture became problematic when the supply chain broke down and work that was to be completed by other major suppliers arrived in Charleston unfinished. . .The problem was Vought had no control over the procurement of those large pieces [from Kawasaki, a Tier 1 Japanese partner in the program]. Boeing, as the prime contractor was responsible for managing those major partners . . . To manage the traveled work efficiently, you need that responsibility . . . That is best done by the prime [contractor].' (Gates, 2008: A1)

Doty blamed Boeing's organizational architecture for the delays.

As Table 2 (Delay No. 1) indicates, Spirit, formerly Boeing Wichita, was also responsible for some of the early delays. This partner was responsible for the forward fuselage of the airplane, including the airplane's cockpit installation and Honeywell, a subcontractor, was responsible for the airplane's flight control systems (Lunsford, 2007).

Boeing managers took a series of steps to address the delays and get the 787 program back on schedule. Broadly, their efforts focused on three major approaches: (1) adding engineers and promoting collaboration through co-location; (2) redrawing the boundaries of the 787 program to bring the major fuselage assembly in-house; and (3) building the necessary tools to improve Boeing's strategic integration capabilities.

*Adding engineers and promoting collaboration through co-location*

Boeing reassigned engineers from its other divisions to the 787 program to take responsibility for the specific parts of the airplane such as electrical systems, structures, and computers (Michaels and Sanders, 2009). Importantly, Boeing engineers' role had gone from being passive observers to active participants. This new approach resulted from McNerney's directive that Boeing managers 'stick their noses into suppliers′ operations.' As Bair observes:

> 'Some of the things that we have learned [from the delays], and this is primarily around structural partners, we had assumed basically that all of the structural partners could do the exact sort of work statement. Bad assumption; some of them were really good at delivering the "whole package" and some of them had some deficiencies.' (Mike Bair, pers. comm., 2008.)

Boeing engineers began to collaborate more intensely with partner firms to resolve immediate issues and avoid future delays. Specifically, Boeing responded by throwing both money (about $2 billion in additional R&D expenses) and people at the problem. It dispatched 'dozens or hundreds of its own employees to attack problems at plants in Italy, Japan, and South Carolina' (Lunsford, 2007: A1). Boeing engineers and production workers were stationed in the factories of Tier 1 suppliers to share their expertise and facilitate integration. Much of the focus and attention was centered on *bottlenecks*—the GA and Vought factories where preassembly was done, as Shanahan publicly discussed.

> 'We′ve had people, whether its supervision helping them with incorporating [design] changes back in Charleston or whether its been folks helping them with their supply chain, that's been ongoing for a better part of the start up of the program [since 2006]. More recently, we just had a higher influx of people into Charleston because you compare the capability and capacity, the limitation is there, it's not at Spirit, it's not at MHI or KHI or FHI. That seems to have the biggest payoff.' (Ostrower, 2009)

In fact, production delays recovered rapidly at Spirit and Boeing managers attributed its quick turnaround to its former Boeing heritage and Spirit's familiarity with Boeing's tools and process (Gates, 2008). Figure 3 is a schematic representation of the changed organizational architecture, and the arrows between Boeing's engineering group and the suppliers' engineering groups represent a marked departure in approach compared with Figure 2.

*Redrawing the boundaries*

In March 2008, Boeing bought Vought's 50 percent stake in GA, forming a Boeing and Alenia joint venture. GA was the staging site where major fuselage sections from the Japanese and Italian partners were preassembled. Boeing attributed inefficiencies with GA for some of the delays.

In a major move a year later (August 2009), not pleased with the progress, Boeing bought Vought's



DOI: 10.1111/j.2042-5805.2012.01050.x

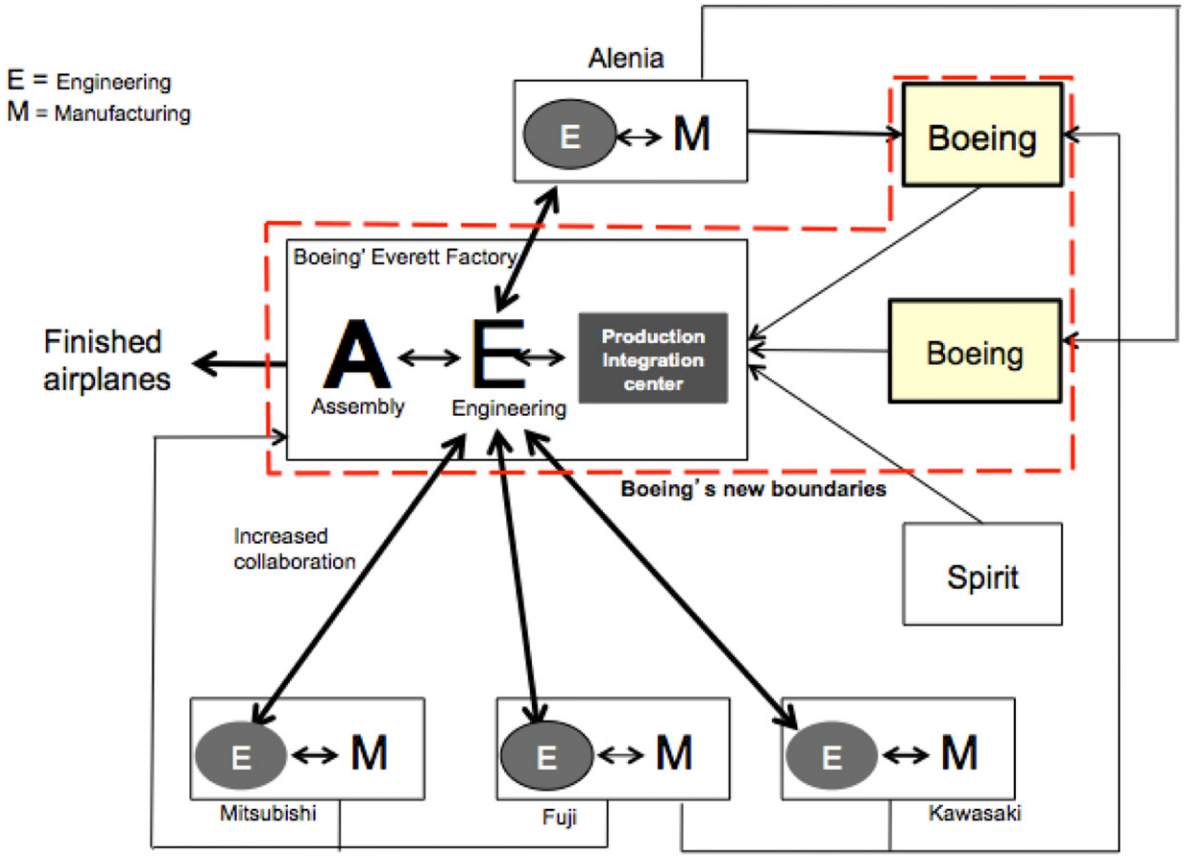


Figure 3. Simplified view of the changed architectural design for the 787 airplane, 2009
Source: Authors' representation of Boeing's approach

Charleston factory, relegating Vought to the role of a supplier of components and subsystems.[6] In December 2009, Boeing dissolved its joint venture with Alenia and took full control of the GA factory in Charleston. Thus, Boeing took over the entire preassembly activities at the Charleston location, a major move that addressed Doty's earlier comments that responsibilities needed to be aligned. To industry observers, this was not a surprise, as Scott Fancher, the next 787 program manager had publicly noted that this might happen:

> 'You know, you get into a situation where either some of the first tiers or their sub-tiers simply aren't able to perform: now there could be a lot of reasons for that, could be that they are in financial stress, could be that technically they've run into a situation they can't handle, or could be the complexity of the production of the product that they've designed is beyond their capability; so we tend to look at the root cause of the nonperformance and how can we help them succeed . . . Clearly as we go forward, we'll look at some rebalancing of work scope as we sort through where work is most efficiently and cost effectively done, but by and large, the focus is on helping our supply chain succeed, not moving the work in a rapid fashion [without completing it].' (Ostrower, 2009)

Boeing reorganized Vought's factory and took responsibility for assembling the airplane's floor grid, which was previously outsourced to Israel Aircraft Industries; this supplier's role would now be limited to delivering components, which were then assembled into full sections by Boeing employees and installed into the fuselage at the Charleston plant. Similar changes were carried out throughout

[6] After taking charge of the 787 program, Pat Shanahan's first major move was to reassign a senior Boeing executive who was in charge of 787 production to oversee all the development activities at the Vought factory at Charleston.



DOI: 10.1111/j.2042-5805.2012.01050.x

the global supply network, to rationalize the production network and redefine areas of responsibility to match Boeing and supplier's capabilities.

*Building tools and routines for integration*

The new global partnership strategy dictated that instead of individual parts, *stuffed* modules or *work packages* would be assembled at Everett. In line with Boeing's blueprint for the 787, the factory was optimized for *snap-fitting* major completed sections. So when incomplete work packages began to arrive (Delay No. 3 in Table 2), the Everett factory was unable to assemble these subsections.

Boeing managers recognized that for the system to work effectively, greater oversight of the supply chain system was necessary, as McNerney had observed. Echoed Scott Carson, CEO of Boeing Commercial Airplanes, 'In addition to oversight [of the program], you need insight into what's actually going on in those [partner] factories . . . Had we had adequate insight, we could have helped our suppliers understand the challenges' [Lunsford, 2007: A1]. In other words, having insight or visibility would have enabled Boeing to predict, not just react to, supply chain contingencies (e.g., Delays No. 3, No. 4, No. 5, and No. 6). According to Ben Funston, one of Boeing's executives in supply management:

> 'On a legacy program you can pretty much walk out into the Everett factory and kind of get a feel for how production's going . . . The reason isn't because that's an all inside make, but basically because we ship in a bunch of small subassemblies and we integrate it all here . . . In the 787, by the time you get here to Everett, you're receiving a few sections of fuselage and wings and we integrate it here . . . So we needed a tool to give us *situational awareness* into the production system and the ability to have early issue detection and real-time problem resolution. If you find it here or even if you find it at the partner before he's getting ready to ship, it's too late.' (Creedy, 2010)

## Creating visibility

To create situational awareness or visibility, the 787 team created the Production Integration Center (PIC) in December 2008. According to Bob Noble, vice president for 787's supply chain, the center's purpose was 'to provide situational awareness, early issue detection, and real-time problem resolution for the 787 Dreamliner production system' (Ostrower, 2009). The PIC is a 5,100-square-foot center that operates around the clock, with translators for 28 different languages (James, 2009).[7] The center was manned by multifunctional teams of experts who specialized in different functional areas pertaining to aircraft design, avionics, structures, technology, assembly, and logistics. The center also continuously monitored conditions around the world (ranging from natural disasters, such as tornados or earthquakes, to political situations like riots, to epidemics like the swine flu), all of which could potentially affect production and transportation of finished fuselage sections to Everett (James, 2009).

The PIC was designed as a centralized facility to help integrate the global product system. First, it helped coordinate problem solving by improving communication and facilitating collaboration among Boeing and partner engineers. For instance, if an engineer at one of the partner sites had an issue, he/she could contact the center to be connected with appropriate Boeing personnel who would help resolve it. Hence, Boeing could now respond to issues by helping suppliers' engineers communicate directly with their Boeing counterparts. Second, as the center's partner call volume increased, managers instituted routines to prioritize them (Creedy, 2010).[8] This provided greater focus and attention to issues that mattered in resolving delays.

Third, the center provided high-definition cameras at partner sites so engineers at partner sites could employ multimedia communications to diagnose and address problems. As Michaels and Sanders (2009: 7) observed,

> 'Suppliers as far afield as Australia, Italy, Japan and Russia could call in through translators and show Boeing engineers in the center close-up images of the their components using high-definition handheld video cameras . . . Immediate, multimedia communications have eliminated the problem of unclear e-mail exchanges between distant engineers who work on the opposite ends of the clock.'

[7] The PIC holds 27 workstations, each with three screens, and a huge (40- by 10-feet) video screen in the front of the room, with 24 separate screens that monitor news around the world, report on global weather patterns, provide real-time information on production issues with each supplier, highlight the health of 787-related computer servers, and display shipping schedules for the four giant Dreamlifters (converted 747s that transported 787 parts to Everett) (James, 2009).

[8] Funston, one of the senior executives, observes, 'If we came in and said this is an absolute line-stopper for the program, then everyone stops what they are doing at that site and realigns to that priority' (Creedy, 2010).



DOI: 10.1111/j.2042-5805.2012.01050.x

Table 3. Processes and routines developed at the PIC to foster integration

| Types of processes instituted | Functional goal of the processes and routines | Learning that resulted from employing the processes |
|---|---|---|
| **Integrating production**<br>A set of processes and routines developed to track production activities at Tier 1 partners. | Gain greater visibility into partners' activities. The emphasis was on problem diagnosis. | Generating visibility, Boeing is able to surface problems before they disrupt the schedule. Such visibility is currently limited to Tier 1 partners. Boeing could establish PIC-like facilities at other factories, which should enable it to gain visibility into Tier 2 suppliers. |
| **Coordinating calls for assistance**<br>A set of routines to (1) manage and catalog incoming calls for assistance from Tier 1 partners, and (2) track and monitor calls. | Enable partners to contact Boeing for expertise to help problem diagnosis and resolution. The emphasis is on enabling 'knowledge' visibility for partners.<br>Created a sense of urgency on the part of PIC managers to resolve problems at partner sites. | Using data on incoming calls, managers were better informed about partner challenges and resources they need to resolve problems.<br>High definition video cameras provided rich data on the artifact and the context needed to make decisions. Such rich communications made problem diagnosis and resolution more productive.<br>If certain calls were not resolved within a given time period, they were escalated to senior managers for resolution. |
| **Coordinating air transportation**<br>A set of routines to manage a Boeing fleet (modified 747s airplanes) to transport preassembled sections. | Assist with material flows among partners and between Charleston and Everett. The emphasis is on integrating the supply chain. | As the system achieved a modicum of stability, the center's primary responsibility shifted to managing the air transportation fleet to transport preassembled sections from partners to Boeing facilities. |
| **Monitoring potential disasters**<br>A set of routines to monitor/assess events that could potentially disrupt the global supply chain. | Predict rather than react to potential disruptions. The focus is to ensure that supply chain linkages are maintained through alternate arrangements, if needed. | The system worked as designed. The PIC center keeps senior management and partners informed of disruptive situation when they happen. |

Using such visual access to partner sites and rich information, Boeing developed a variety of proprietary routines to gain visibility and monitor the system.[9]

Lastly, the center took responsibility for transporting structural sections throughout the network and ensuring that they arrived at Everett on schedule. Boeing managers recognized that effectively managing the transportation of large fuselage sections was critical for system effectiveness. With this new air transportation system, Boeing minimized work in process inventory (and related carrying costs) by reducing the time it took to transport large fuselage sections for assembly at Everett. This approach was in line with Boeing's stated goal of becoming a lean manufacturer as described in Boeing's 2016 vision document. Table 3 details the routines the center developed to create visibility. Also the PIC is represented as an important addition as shown in Figure 3.

[9] For instance, managers created routines for recording and monitoring phone calls for assistance from partners, visually mapping and updating production status at partner factories in real time. They also developed simulation routines to understand system behavior when faced with major disruptions.



DOI: 10.1111/j.2042-5805.2012.01050.x

*The evolution of the PIC*

Over time, the type of calls and volume received changed, and the center's role evolved. Initially the incoming calls focused on resolving aircraft design issues between engineers at partners and Boeing engineers, and this was then followed by incoming calls focusing on production-related issues. To address them, first the center was initially staffed with multidisciplinary teams of engineers representing major aircraft systems. Then it was organized to support each Tier 1 supplier to handle production-related issues (i.e., the groups within the PIC who worked mostly with a specific supplier and handled integration problems). As the aircraft design and production-related issues were slowly resolved, the center took requests for the rapid delivery of critical parts needed at partner factories in addition to scheduled transportation of preassembled sections. It was then reorganized to address final assembly issues at Everett.

The center served as the *mission control* for the 787's global supply chain using its proprietary routines. With time, Boeing has reduced the number of its engineers co-located at partner sites and the resources allocated to the PIC. Industry experts concur that the center was pivotal in stabilizing the 787's supply chain as measured by declining travelled work (Ostrower, 2009). Travelled work represents work that should have been completed by the supplier but, given the schedule requirements, was not accomplished there but nevertheless was shipped to Everett for Boeing workers to complete. After almost three years of delay, Boeing delivered a 787 airplane to launch customer All Nippon Airways (ANA) in September 2011.

## DISCUSSION

Our intent was to understand how firms integrate activities in *globally disaggregated* complex NPD projects. Our analysis suggests that the lead integrator, Boeing, faced challenges pertaining to three distinct components of integration. Boeing recognized they needed two types of visibility to address these integration challenges and invested in the necessary tools to effectively increase visibility.

### Components of integration

Boeing faced integration challenges relating to: (1) design integration; (2) production integration; and (3) supply chain integration.

*Design integration*

This pertains to how Boeing divided and distributed major airplane design-related tasks to partners, based on an initial assessment of partner capabilities and expected coordination costs. Boeing managers felt that the 787 airplane program merited a global partnership model, which was broadly in concordance with its intent to transform its identity to become a *global large-scale systems integrator*. Also, Boeing was interested in mitigating financial and marketing risk and securing IP rights for composite technology.[10]

One criterion Boeing employed to allocate tasks involved partners' underlying competence to implement a complex program: three major Japanese firms had worked with Boeing designing wings for the 777 and 767 airplanes, programs dating back to the 1980s, which made them ideal partners. Boeing's relationship with Alenia, the Italian manufacturer, also dated back to the 1980s; moreover, Alenia possessed expertise in specialized composites that Boeing needed (Mike Bair, pers. comm., 2008).

The 787 program differed in one important respect. In the past, Boeing had provided detailed specifications, but for this program it chose to supply only broad design parameters; partners had to use their own expertise to design and build major structural sections of the airplane. Boeing assumed that the chosen partners would have the requisite competencies to do design and integration work and build preassembled sections, but this assumption would prove invalid. Bair conceded, 'We had assumed basically that all of the structural partners could do the exact sort of work statement. [This was a] bad assumption' (Mike Bair, pers. comm., 2008). Thus, when some partners were unable to perform as expected, the program faced delays.[11]

[10] While task assignment (who does what) represents a high-level decision choice (e.g., wings are to be made by Mitsubishi) and is relatively simple to envision, it is generally harder to achieve at the activity level (e.g., should Mitsubishi or Fuji be responsible for designing how to join the wings to the center wing box?).

[11] *Ex ante*, it appears that the tasks performed by Vought and Alenia were more complex and subject to greater uncertainty than those performed by the Japanese partners. Thus, while the Japanese were largely responsible for delivering subcomponents, along with building parts of the composite fuselage, Vought and Alenia, were responsible for *stuffing* them, a task that Boeing's partners had never done before. Also, as Bair notes, the Japanese partners were admired for their disciplined approach, something that Boeing's U.S. and Italian partners seemed to lack.



DOI: 10.1111/j.2042-5805.2012.01050.x

Another criterion for allocating tasks was designing a system that reduced coordination costs. As the program unfolded, it became clear that GA and Vought factories were vulnerable to misalignment issues caused by organizational architecture (see Delays No. 4, 5, and 6). While they integrated major subsystems from Tier 1 partners, they lacked the disciplinary authority when incomplete subassemblies arrived in Charleston. This was essentially the complaint that Doty, Vought's CEO, had made when he noted it was Boeing, not Vought, who was responsible for managing other Tier 1 partners.

Our analysis suggests that design integration includes both short- and long-term components. In the short term, the airplane has to be delivered to waiting customers and decisions regarding the realignment of tasks allocated to partners followed that imperative. Faced with mounting delays, Boeing bought out Vought's stake in GA. Prior to the acquisition, Boeing co-located numerous engineers at Vought and Alenia to support them. As co-located managers assessed partner capabilities, they came to understand the interdependencies between partners. In the longer term, however, as efficiency considerations become more salient and the production system stabilizes, Boeing could consider externalizing its factories at Charleston. Boeing's Vision 2016 mission statement called for precisely such a transformation.

Although the six Tier 1 risk-sharing structural partners might have worked together to achieve better integration, in reality Boeing, as the central actor, intervened to make changes. Using its bargaining power, the company changed the division of labor to achieve better task allocation, reflecting studies of large-scale integration regarding the final assembler's central role in reconfiguring complex systems (cf. Argyres, 1999). Given the uncertainty of the nature of interdependence and the lack of precise information about partners' abilities, it is unclear whether Boeing could have achieved better design integration *ex ante*. Boeing has had relationships averaging 30 years with its six structural partners, which suggests that when qualitative changes are introduced into buyer-partner relationships (in this case, moving from *build-to-print* to *build-to-performance* model), *previous stocks of RSA may not be sufficient to make task assignment decisions of importance*.

*Production integration*

This integration pertains to how production-related tasks, including product design and manufacturing, are coordinated across partners and the final assembler. As Bair noted earlier, Boeing wanted each partner to design and manufacture subassemblies in order to align the *design and build* aspects at partner factories (i.e., partners and not Boeing were better positioned to optimize their factories for efficient production). Boeing's logic was to encourage a *thick interface* between design and build at partner factories instead of having them rely on Boeing as in previous programs (see Figure 2). However, in practice, the partners not only had to optimize their own factories, but also had to integrate their efforts with the lead integrator and other partners. Boeing had generated this skill in past programs, but their partners had not, since in the old build-to-print regime, suppliers worked mostly from codified knowledge Boeing shared with them. McNerney recognized this when he directed Boeing to 'poke their nose into supplier operations,' a message that was contrary to the initial program design approach. Importantly, the 787 team recognized that it needed a tool that would give them insight and visibility into partner facilities, as Scott Carson, the CEO of Boeing Commercial, had observed.

Achieving production integration required a number of changes. First, Boeing added more engineers and machinists, who then became active participants and collaborators instead of passive observers (contrast Boeing's role in Figure 3 versus in Figure 2). Second, hundreds of design and production engineers were co-located at partner factories, bolstering partner expertise, though it appears that the improvement in production integration came from their knowledge of Boeing's processes and ability to highlight partner deficiencies. These engineers are akin to *boundary spanners* (to use the terminology of Mudambi, 2011) who are recognized and credible to both Boeing engineers as well as partner engineers. They play a critical role in knowledge transfer across boundaries within a MNC firm and often across firms.

Third, managers created a unique IT-enabled centralized integration center (i.e., PIC) as described in detail earlier. This center was staffed with multifunctional teams and they instituted processes and routines for prioritizing and attending to calls so that requests for help from partners were dealt with in a timely manner. Such processes and routines are akin to what (Carlile, 2002) has described as *boundary objects* that are critical for knowledge transfer across boundaries. Boundary objects represent 'a means of representing, learning about, and transforming



DOI: 10.1111/j.2042-5805.2012.01050.x

knowledge to resolve the consequences that exist at a given boundary' (Carlile, 2002: 1526). They instituted routines that created a sense of urgency on the part of Boeing personnel to respond to requests by tracking and monitoring calls, accessing senior managers if needed. The center also included tools that established the necessary *contextual common ground* (Srikanth and Puranam, 2011) needed to resolve issues such as the use of translators and video cameras.[12] Overall, these routines enhanced joint problem solving between Boeing and its structural partners by increasing visibility.

*Supply chain integration*

Consistent with Boeing's relations with its structural partners, we characterize the supply chain as the purchasing operations and relationships between a firm and its first tier suppliers including buyer-seller alliances and partnerships (Cavinato, 1992; Blocher, Lackey, and Mabert, 1993). Effective supply chain integration is critical for network effectiveness and encompasses the integration of information flows, physical flows, and financial flows between a firm and its supply chain partners (Rai, Patnayakuni, and Seth, 2006). By design, Boeing chose to air transport preassembled sections removing slack in the system, which made supply chain integration a priority for the airplane's production.[13]

Supply chain integration challenges loomed large during program implementation (see Delays No. 3 and 4 in Table 2). To transport preassembled sections, processes and routines were instituted at the centralized integration center. One set was aimed at scheduling the airplanes Boeing used to transport sections to the preassembly factories in Charleston, and between South Carolina and Everett. Another set tracked potentially disruptive events (natural disasters such as earthquakes) so that appropriate actions could minimize their impact on material flows throughout the 787 network. These routines also enabled Boeing to monitor the work-in-progress at the partner factories enabling it to *predict* potential delays and address them in order to maintain the schedule. While in theory Boeing could have outsourced transportation of large fuselage sections, given the specialized nature of these assets (the ability to design and modify 747 jumbo jets), Boeing decided to do this in-house.

**Visibility mechanisms for integration**

As the 787 program unfolded, Boeing managers recognized that they needed two types of visibility to address the integration challenges they faced. On the one hand, partners needed access to Boeing's and other partners' expertise so that appropriate knowledge could be obtained for diagnosing and resolving problems. On the other hand, Boeing needed awareness of partner activities throughout the network to fully comprehend the issues confronting them.

We term the first type of visibility *knowledge* visibility and the second *activity* visibility. Activity visibility provides the contextual and tacit information necessary to solve problems and is helpful in monitoring partner activities in real time throughout the entire network. Knowledge visibility makes visible the locus of expertise that is available throughout the network. Without such visibility, partners find it difficult to locate the expertise needed to address issues confronting them in a timely fashion. Activity visibility and knowledge visibility, as discussed here, are independent constructs although they often coexist in practice.

To carry out effective design integration, the lead integrator needs to better understand the nature of interdependence, assess partner competence, and reassign tasks as issues arise. Both activity visibility and knowledge visibility help promote such an understanding and, in the process, enable better design integration. In production integration, the nature of the integration effort shifts toward addressing issues that often arise at the nexus of product design and manufacturing. Knowledge visibility helps access the expertise required from the network to solve such issues. Activity visibility promotes building contextual common ground between the partner and lead integrator (the one with the expertise) and helps the engineers better understand the tacit components involved in finding

[12] The need for context-specific knowledge to coordinate across locations is referred as contextual knowledge, contextual awareness, or contextual common ground in the academic literature (Kraut *et al*., 2002; Olson *et al*., 2002). But Boeing managers internally refer to such knowledge as situational awareness.

[13] With time and greater stability in the production network, supply chain integration has increased in importance. Such integration is likely to become even more complex as Boeing ramps up production from the current production of two planes per month to a planned rate of 10 a month. Boeing opened a final assembly plant at its Charleston location next to the two factories it acquired from Vought and Alenia, modeled after its final assembly plant in Everett.



DOI: 10.1111/j.2042-5805.2012.01050.x

a solution.[14] Therefore, both activity and knowledge visibility play an important role in production integration. With regard to supply chain integration, the onus is on predicting likely disruptions and addressing them before they ripple across the network. Activity visibility enables monitoring partner factories to predict potential disruptions that can occur. Knowledge visibility, in this context, can help engineers find ways to ensure that schedules are synchronized and deliveries are prioritized so that disruptions in the supply chain are minimized. In summary, both activity visibility and knowledge visibility are important in achieving all the three components of integration.

## Tools for integration

Boeing used a combination of traditional and novel tools to enable visibility of both kinds. These included: co-location, the PIC, and vertical integration.

### *Co-location*

In general, co-location provides both high levels of contextual common ground and unconstrained opportunities for rich face-to-face interactions, thus enabling a lead integrator to achieve activity visibility. Through such visibility, the lead integrator can assess suppliers' competence, understand the nature of interdependence, and engage in joint problem solving. In other words, with activity visibility, the lead integrator could redesign/reassign tasks to facilitate better design integration. The quality of activity visibility that co-location permits makes it an important tool for achieving production integration (see Table 4 for details).

In our context, despite its initial organizational architecture for the 787 program, Boeing discovered that some co-location was unavoidable, especially during the early phases. Co-locating Boeing personnel at partner factories aided integration by providing Boeing the ability to see partner activity and assist them in accessing expertise at Boeing. In other words, co-located Boeing personnel were able to deeply understand the issues partners faced in their respective factories and knew whom to contact at Boeing Everett to help address such issues. Co-locating personnel also provided Boeing the ability to assess partner competence and willingness to adapt and learn, providing a *partner monitoring* mechanism.

### *Centralized integration support center*

Boeing found one reason for program delays was that some of its partners were unable to complete the task assigned them in a timely manner, frequently because of cascading interdependence between the partners. The partners needed the knowledge regarding whom to contact at Boeing to help fix issues and Boeing, for its part, needed to know which of the partners needed assistance. Additionally, Boeing needed a mechanism to access the tacit knowledge regarding the partner's context to better appreciate and help partners solve problems.[15] In other words, although Boeing, as the prime contractor, was ideally suited to facilitate *inter-partner* integration, it was unable to do so without the necessary activity visibility and knowledge visibility.

Through the centralized center, Boeing was able to gain information about partner activities and the situational context and the partners, in turn, had a way to access Boeing's expertise. The center promoted activity visibility through the use of high-definition cameras and artifact-based communications. Based on the requests for assistance from distributed partners, the lead integrator mobilized and directed resources and expertise to solve problems at partner factories, achieving production integration. In fact, the center centralized and prioritized communications and routed problems to potential solvers across the network. In other words, the center (and the specific processes and routines that underlie it) promoted both activity and knowledge visibility that, in turn, enabled design (i.e., task reassignment) and production integration. The activity visibility also gave Boeing access to information needed for better supply chain integration. Some examples of how both activity and knowledge visibility generated

[14] Suppose Supplier X has Problem P. Supplier X needs to search to find out who can help solve this problem. Knowledge visibility allows Supplier X to find out that Engineer Y is the lead integrator or another partner can solve this problem. In order to solve this problem, Y needs activity visibility because X cannot articulate all the tacit contextual information that is necessary to solve the problem.

[15] Both these issues were new to the 'build to performance' regime instituted with the 787 program. Boeing had initially assumed that it was best to resolve integration issues by tightly coupling design and manufacturing at partner sites. However, this approach failed to address the need for integration between partners and Boeing and among partners when program implementation started.



DOI: 10.1111/j.2042-5805.2012.01050.x

Table 4. Integration components and integration tools in the 787 program

| Integration Tools | *INTEGRATION COMPONENTS* | | |
|---|---|---|---|
| | DESIGN INTEGRATION | PRODUCTION INTEGRATION | SUPPLY CHAIN INTEGRATION |
| **VERTICAL INTEGRATION** | Provides the authority needed to align tasks and responsibilities. | Can enforce actions unilaterally to increase visibility of activities at geographically distributed facilities within the firm. | Can enforce actions to increase visibility of actions to predict issues.<br>Can modify/change scheduling priorities at company-owned facilities for smoother supply chain operations. |
| **CO-LOCATION** | Promotes visibility of activities that allows for evaluating interdependences between actors and the lead integrator. Promotes knowledge visibility to understand competencies of the supplier. | Promotes visibility of activities, which helps the prime integrator to better understand partner challenges in carrying out the distributed tasks.<br>Co-located personnel can act to promote knowledge visibility by helping partners find the required expertise at Boeing to resolve problems. | Not used in our setting. |
| **The PIC** | | | |
| Artifact-based communication using high-definition cameras | Allows for visibility of activities using rich data, but likely to be less effective when cutting-edge technology programs are involved. | Visibility of activities allows for effective problem diagnosis and resolution across geographies, and cuts days out of the problem-solving loop. | Could communicate the severity of damage (using rich data) at partner facilities in the wake of a natural disaster or help describe production problems (using rich data) that could impact the schedule. |
| Resource (expertise) mobilization | Not applicable. | Enables the integrator to direct resources and expertise to solve problems at partner sites. Partners gain visibility to knowledge at Boeing. | Enables integrator to direct resources available at Boeing to help the supplier manage activities better to resolve potential ramp-up problems. |
| Centralization, prioritizing activity, and monitoring to follow-up for resolution | Not applicable. | Ensures more important problems are resolved before smaller problems are tackled.<br>Creates a sense of urgency at Boeing to respond to requests for assistance. Also, top management can be informed or looped in, if needed.<br>Highlights integration needs (such as approvals for design changes in our setting). | Ensures that schedules are synchronized and deliveries are prioritized to ensure that disruptions are minimized.<br>Centralized tracking and monitoring enables effectively closing the loop on supply chain issues. |



DOI: 10.1111/j.2042-5805.2012.01050.x

by the center were important in achieving design, production and supply chain integration are illustrated in Table 4.

*Vertical integration*

Faced with short-term pressures and the inability of the Vought and GA factories to resolve issues rapidly, Boeing acquired these facilities, using its authority as the prime contractor for bargaining clout. Despite having significant prior relationships with Boeing and being risk-sharing partners, these partners were reluctant to reorganize their factories to generate the required action visibility. Some of the partners also lacked the authority to direct the actions of other Tier 1 partners while still being responsible for integrating their work. The traditional role of vertical integration is that activities in subunits could be reorganized by recourse to fiat, which is how Boeing gained the authority to reorganize the factories in South Carolina. Boeing then opened them up for closer scrutiny, thus improving activity visibility, which facilitated all three integration components.

Figure 4, in a simplified framework, highlights the interrelationship among the three components of integration, the mechanisms, and the tools discussed earlier. Vertical integration enables integration of all three components primarily through action visibility. Both co-location and developing a centralized center enable integration of all components via both activity visibility and knowledge visibility. However, as illustrated in the different weights of interconnections, the knowledge visibility created by a centralized center (i.e., the PIC) appears superior to that solely dependent on co-locating engineering personnel at partner facilities, because knowledge visibility created by a co-located engineer is limited by his/her ties in the network. However, a centralized system can help a partner gain access to experts throughout the network, giving the center the ability to rapidly match knowledge sources with where they are required. However, activity visibility generated by a centralized center is not as detailed as that generated by co-locating personnel, since being immersed in the context allows for much richer interactions than using tools such as video cameras. As shown in Table 4, though knowledge visibility generated by co-location is also useful for production and supply chain integration, co-location's impact is less important for these in our setting, primarily because the centralized center took over many of these functions.

## CONTRIBUTIONS, LIMITATIONS, AND CONCLUSIONS

We began with the premise that NPD programs that involve cutting-edge technologies distributed across

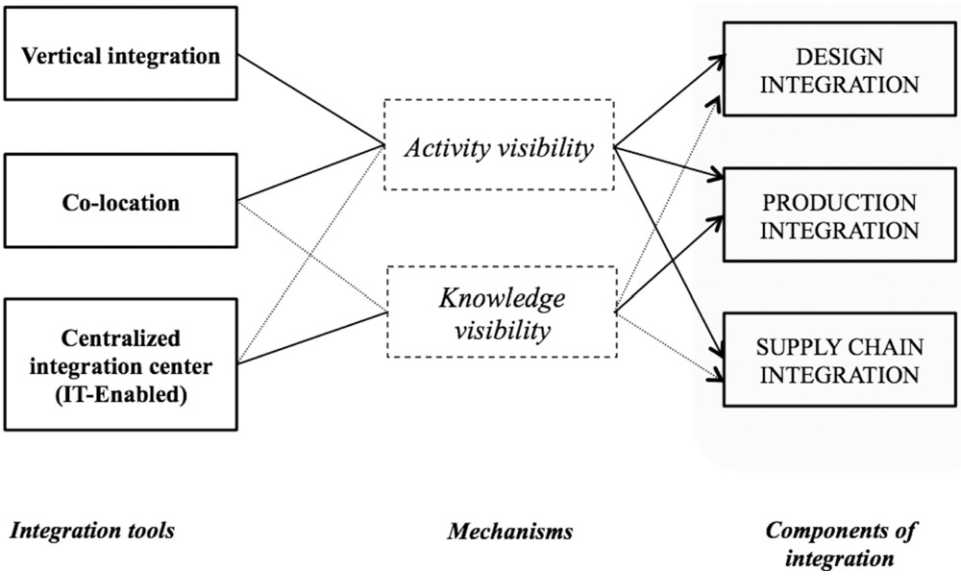


Figure 4. A proposed framework for achieving global integration



DOI: 10.1111/j.2042-5805.2012.01050.x

*both* geographic and firm boundaries presented unique integration challenges. In this case, technological uncertainty precluded modularity, and co-location of assembler and supplier engineers (as has been done in the past) is expensive. Prior work on buyer-supplier relationships has been silent on how to manage the impact of geographic dispersion, except to point out that greater dispersion may result in poor integration outcomes (Dyer, 2000). The extant international business research has emphasized how the level of unified authority characterizes the integration issues within MNEs (Mudambi and Navarra, 2004). However, such authority is generally absent in buyer-supplier relationships. It is from this context that this article makes novel contributions.

First, to the best of our knowledge, this is the first study that provides a holistic understanding of what constitutes achieving integration from the context of a complex NPD program carried out across geographic and firm boundaries. We found three distinct components of integration capabilities. Prior studies of complex NPD programs primarily highlighted 'production integration' challenges and neglected the design and supply chain integration issues faced by firms using a globally distributed partnership model. Our finding suggests that as firms grapple with production-integration challenges, they realize that these challenges can arise from improper or poor design integration. In large, complex products, all three integration components may tax a firm's ability to achieve integration, leading to system instability.

Interestingly, all three components gained salience at different times during the program implementation. The division of labor decisions made as part of design integration needed to happen first. Poor decisions at this stage can lead to production integration problems. In novel and complex systems, it may be impossible to achieve perfect design integration *ex ante*; any observed production integration problems are fixed first by achieving better design integration. Supply chain integration issues are typically faced after the product design has stabilized and many technical issues in manufacturing are ironed out. Supply chain integration leverages the activity visibility generated for production integration and moves toward predicting and preventing integration issues rather than reacting to them.

Second, in contrast to past research focused on co-location and/or RSA as the primary tools for achieving integration, this study highlights the role played by a dedicated, centralized center specifically designed to achieve integration. As a tool, the integration center has become the brain behind Boeing's integration efforts. Specifically, our findings highlight the importance of two distinct types of *visibility* as critical mechanisms underlying integration.[16] As a centralized entity, the center increases visibility (activity and knowledge), thus enabling the prime contractor to achieve and maintain integration. Its effectiveness can be seen in improved integration performance and reduced co-location needs.

Third, analyzing the center's role helped clarify interrelationships among such integration tools as co-location, RSA, and authority. As noted, co-location is difficult and expensive to achieve in a globally distributed complex NPD project, and RSA's effectiveness as a tool is unclear when task requirements change. Our findings point to the indispensability of *some* co-location in such situations regardless of cost; we also found that co-location varied by partners' ability to accomplish their assigned tasks (e.g., Vought and Alenia required greater co-location than Spirit). As routines were established to promote production and supply chain integration to stabilize the system, the amount of co-location was gradually reduced, suggesting that a dedicated integration center can largely (but not completely) substitute for co-locating personnel at partner facilities.[17]

Also, past research has not explicitly examined whether co-location and RSA are complements or substitutes, though they are both important tools to achieve integration. Co-location enables visibility of activities at partner facilities and limited visibility of knowledge located in the two firms. RSA or social integration over time leads to increasing knowledge visibility. Specifically, RSA cannot fully substitute for co-location in complex projects because it cannot provide activity visibility. In this case, the changed task (build-to-performance versus build-to-print in earlier programs) further constrained RSA effectiveness. The integration center, however, was designed to provide both visibility of knowledge and visibility of activities.

[16] Prior work has referred to co-location, RSA, and normative and social integration as 'integration mechanisms.' To us, these represented tools and not mechanisms. Each of these tools increases visibility between the partners, which is the mechanism by which these tools facilitate achieving integration.

[17] One can think of the relationship between co-location and the integration center similar to the relationship between capital and labor in a (Cobb-Douglas) production function. Some co-location is necessary for efficient functioning, but the integration center can effectively substitute after a threshold minimum level.



DOI: 10.1111/j.2042-5805.2012.01050.x

Fourth, regarding the role played by authority, our preliminary findings add limited empirical traction to the largely theoretical debate over the role of authority in the knowledge-based view of the firm. The defining question in the theory of the firm literature is the boundary choice between pure markets and hierarchies. Kogut and Zander (1992, 1996) assert that firms are communities that enable knowledge exchange and coordination based on continuity of association and common identity, leading to a common language and higher order organizing principles. In contrast, Williamson (1991) argues that authority is important because it prevents haggling over gains/costs and reduces transaction costs.[18] Empirically distinguishing these assertions is difficult in practice because a firm is both a boundary of association *and* authority. Hence, it is not surprising that the empirical evidence is mixed.[19] The 787 program involves risk-sharing partners and lies in the *swollen middle* (Hennart, 1993) between pure markets and hierarchies. Thus, it provides an opportunity to examine the assertions raised earlier.

When Boeing acquired the Vought and GA facilities, the unified authority enabled the Charleston factories to merit the attention of the internal buyer in Everett, in order to approve coordination changes and integrate production, a task with which the external supplier had struggled. Integration also enabled investment in visibility-enhancing mechanisms in which some external suppliers were reluctant to invest. Also, Vought's Doty had complained about having the responsibility to integrate with other Tier 1 structural partners without the authority to mandate any changes, which technically should not have been a problem since the partners' incentives were aligned toward swiftly achieving effective integration. Our findings, therefore, suggest that authority (or bargaining power) may be necessary in generating requisite visibility for integrating activities. A dedicated integration center, such as the PIC, is only as useful as the visibility it helps generate.[20] This suggests that the visibility necessary for coordination is generated more easily in the presence of authority, a point that needs validation in future empirical studies.

Finally, these assertions have some very interesting implications for a firm contemplating a global strategy. On the one hand, researchers have suggested that the *raison d'être* for the MNE is to leverage economies of knowledge and learning across different geographies (Bartlett and Ghosal, 1989; Mudambi, 2011). An MNE that truly depends on integration across geographies for its competitive advantage is more likely to succeed if the headquarters played a strong role. On the other hand, a strong headquarters challenges subsidiary autonomy and flexibility (Birkinshaw and Hood, 1998; Mudambi and Navarra, 2004). So the international business research suggests that given such trade-offs, middle positions are unsustainable. But our findings suggest middle positions are sustainable if the HQ managers have the tools to generate visibility across the MNE network of subsidiaries.

## Study limitations

This is one of the first inductive studies to examine a complex globally distributed NPD project. While our choice of program and industry may limit the generalizability of the findings, it has enabled us to take a more fine-grained approach to analyzing how global integration capabilities emerge in practice. Such detail would be difficult, if not impossible, to capture through large sample studies (Poole and Van de Ven, 1989). Given our objective of understanding the boundary conditions of existing theory, this approach was well suited to our research question. Also, some of the processes and mechanisms highlighted are generalizable across other complex globally distributed programs.

We recognize that there are numerous other important issues to the success of venturing into an NPD in a globally disaggregated supply chain. Given our interests and the thrust of the special issue, we restricted the scope of the article and focused extensively on activity coordination among actors and deliberately ignored other important aspects of new product development (such as financing models for

[18] Building on Williamson's work, Argyres (1999: 168) has speculated that 'some sort of hierarchical mechanism may be needed in the early stages of systems development and adoption in order to overcome inherent transaction cost and bargaining problems.'

[19] Some studies have found little difference between within-firm integration versus between-firm integration (Helper *et al*., 2000), while others showed that within-firm integration is superior (Almeida *et al*., 2002).

[20] From a variety of motivation considerations, partners may limit their facilities' visibility to the systems integrator. Co-location is one means of overcoming such motivation challenges, as the collocated integrator's engineers can monitor the activities of partners. However, in a globally disaggregated program, this is a costly solution. In these cases, authority could remove potential impediments to achieving such visibility.



DOI: 10.1111/j.2042-5805.2012.01050.x

complex projects, project management issues, supplier selection, and the role played by risk in the initial design and subsequent reorganization of the airplane's program architecture). The aspects of the program not examined here are interesting avenues for future research.

Our primary informants were Boeing employees. Although we interviewed Boeing personnel who were directly involved in supplier integration issues at Vought, both before and after its takeover by Boeing, we did not interview other major suppliers, which is a limitation to our data. However, since we relied on media reports and comments by industry observers, we provide a balanced and accurate understanding of how events unfolded. Finally, we were not privy to other tools Boeing may have used to manage the program. Given the importance and complexity of this topic, it would be an excellent avenue for future research.

Past research has suggested that when a product's architecture is modular, knowledge integration from external sources is less difficult (Baldwin and Clark, 2000; Brusoni *et al*., 2001). But technological uncertainty and an incomplete understanding of interdependencies preclude modularity and increase misalignment risk (Ethiraj and Levinthal, 2004). It is possible that once the 787 production system reaches a level state and when interdependencies are better understood, greater modularity may be achieved. In other words, modularity may not be initially designed in a complex system; it may emerge with time, as the interdependencies are better understood. This topic should be reviewed for possible research when Boeing introduces its 787 derivate, the 787–9, within the next few years.

## CONCLUSION

This article examined how to integrate globally distributed complex innovative projects by studying the Boeing 787 *Dreamliner* program. Whereas prior work has emphasized the need for co-location between partners and the formation of individual-level personal relationships to achieve coordination and alleviate opportunism concerns, such tools are not readily adapted to integrating work distributed across geographic and firm boundaries. We find that integration is facilitated by enhanced visibility between assembler and partners regarding the context of work and the locus of knowledge; we suggest that the integration tools identified in prior work effectively increase such visibility, and we argue how a dedicated integration center may increase visibility.

We also find that bargaining power is important to motivating partners to take actions that enhance visibility across firm boundaries. Taken together, these findings imply that (1) enhancing visibility is the mechanism that underlies all integration efforts and (2) under conditions of uncertainty, authority (or a close substitute), is necessary to enhance visibility and thereby achieve coordination even when incentives are aligned. These findings inform the lively debate between the transaction cost-based perspective and the knowledge-based view of the firm by suggesting boundary conditions for the latter.

## ACKNOWLEDGEMENTS

We thank the Boeing executives for taking the time to share their insights. Specifically, we thank David Smukowski for connecting us with various executives at Boeing. We also thank Markus Becker, Anand Nandkumar, Torben Pedersen, seminar participants at the Copenhagen Business School, and the associate editor and three anonymous reviewers for their feedback in improving the article.

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DOI: 10.1111/j.2042-5805.2012.01050.x

# The Challenge of Innovation in Highly Complex Projects: What Can We Learn from Boeing's Dreamliner Experience?

**Article** *in* Project Management Journal · March 2016

DOI: 10.1002/pmj.21579



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PAPERS

# The Challenge of Innovation in Highly Complex Projects: What Can We Learn from Boeing's Dreamliner Experience?

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## ABSTRACT

Understanding the link between project complexity and innovation is highly pertinent. Yet, the challenge of innovative complex projects has received limited research attention and little theory development. This article provides a retrospective analysis of the difficulties experienced by Boeing during the development project of its highly innovative Dreamliner aircraft. Eventually successful, this project suffered extensive delays and cost overruns. The article analyzes the project's complex nature of innovation, while using several frameworks to provide an integrative view of its challenges and suggesting possible alternative ways to address them. Insights for complex project teams and future research directions are offered.

**KEYWORDS:** aerospace; innovation; complexity; project management; complex project and program management; Boeing 787 Dreamliner

Project Management Journal, Vol. 47, No. 2, 62–78

Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pmj.21579

## INTRODUCTION

Boeing Corporation, which was founded in 1916, has become one of the world's largest manufacturers of commercial aircraft, ranking now 27th on the Fortune 500 list. On September 26, 2011, Boeing publicly announced the delivery of its first 787 Dreamliner transporter to its first customer, All Nippon Airways. That event took place almost 40 months later than originally planned, after a long series of unexpected delays. The actual development cost of the project was estimated at about US$40 billion and was "well more than twice the original estimate" (Mecham, 2011). Adding to the difficulty was the discovery of a malfunction a year later in one of the aircraft's lithium batteries, which caught fire after takeoff. These problems led to months of grounding, imposed by the FAA (Federal Aviation Administration), of the entire Dreamliner fleet already in service.

Boeing's vision for the Dreamliner was to make it one of the most advanced commercial aircraft ever built and one of the most efficient to operate. However, its late delivery and early service problems were particularly troubling for a large corporation like Boeing, which is highly regarded as a leader in the aerospace industry and one of the world's most experienced aircraft manufacturers. However, the Dreamliner's late debut also provides an opportunity for the aerospace industry, and the research community at large, for retrospective in-depth learning.

In this article, we analyze the challenges that Boeing faced in this project and the lessons it learned while coping with them. By taking an innovation management perspective, our analysis offers ways to explain Boeing's experience, and possible ways to avoid similar failures in the future.

Our conclusion is simple. Boeing's delays and other problems *could have been minimized, if not prevented*. More important, a careful early analysis of the project's *innovation* challenges and potential difficulties might have predicted many of the problems that followed, and perhaps avoided some of Boeing's losses, including the resulting reputational damage.

After discussing our research method, the third section outlines the story of the Boeing 787 project.[1] The case story section describes the project's vision and the decisions made by the company through the project life cycle, then outlines the project's challenges and describes the project's development history, including the actions taken by the company in response to its delays. The next section, which is dedicated to innovation, includes a retrospective analysis of

[1]Please note that for consistency in this article, we use the term *project*, although large projects in the aerospace industry are also often called "programs," as they are indeed a collection of related projects (PMI, 2013).

the project's innovative challenges and a discussion on how these problems could have been avoided, or at least mitigated. We engage recent models of innovation and complexity, and point out where more theory development is needed. We conclude with a list of lessons that may be applied in future, large-scale strategic innovation projects, and suggest questions for future research.

## Research Method

The Dreamliner project was one of the case studies in a multi-year study of the aerospace and defense (A&D) industry, which began in the 1990s (e.g., Tishler, Dvir, Shenhar, & Lipovetsky, 1996). In 2007, after Boeing announced its first 787 delay, we made the Dreamliner the focus of a dedicated in-depth longitudinal study. Between 2007 and 2013, we collected all publically available articles or posts about the Dreamliner project, as well as Boeing's history and the project's earlier decisions.[2] We systematically coded all material into categories such as business, performance, strategy, technology, planning, control, testing, and so forth. We read and coded nearly 800 articles and posts, and interviewed eight non-Boeing aerospace executives and reporters who offered their non-classified perspectives. When it became clear that studying this project required more than traditional project and innovation expertise, we increased our team by adding experts in supply chain management and operations. We conducted weekly research-team debates, dedicated to a specific category and its theory, and created discussion notes, which were then cross-analyzed to form the basis for our final analysis. Three independent scholars then reviewed our draft and offered comments and suggestions.

## The Dreamliner Project

### *Initial Vision and Plan*

The Dreamliner project was initiated in the early 2000s to take advantage of new technologies, including composite materials and electronic controls, with an effort to reduce fuel costs and noise levels and as a strategic preemptive move to compete with Airbus' 380 program (Useem, 2006). The Dreamliner project was launched in April 2004 with a planned delivery date during the first quarter of 2008. In retrospect, it seems that this schedule was highly unrealistic. By 2008, however, Boeing had already collected a backlog of more than 850 orders, at an estimated value of US$140 billion, which made the Dreamliner the most successful launch of any aircraft in history. A final configuration was selected in September 2005 and the design of major subsystems began in June 2006. The project opened its assembly plant in Everett, Washington, USA, in May 2007; however, its first test flight took place in December 2009, almost 18 months later than expected, and as mentioned, the first delivery took place some 40 months later than planned.

### *Dreamliner's Challenges*

The Dreamliner was designed to be a revolutionary project in many respects: physical characteristics, technology, management style, financing, design and engineering management, quality assurance, and assembly processes. Many of these initiatives were intentionally taken on to benefit from new developments in aviation technology and to speed up design and development; however, as we will show, they posed unexpected challenges for both the company and the project team.

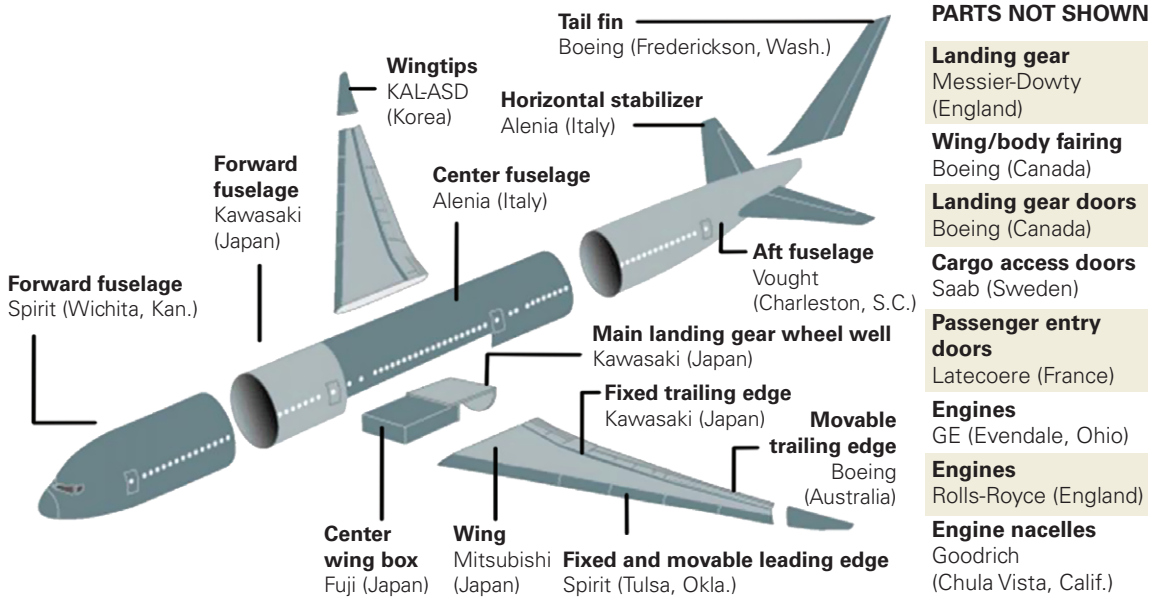
The first major challenge involved designing the aircraft's body using lightweight composite materials (chemical compounds made of carbon). This change was necessary, since the Dreamliner was to provide long-haul transportation for 250 passengers for about a 20% lower fuel cost (Ye, Lu, Su, & Meng, 2005). Although composite materials were not totally new, they were never used to such an extent in a large civilian aircraft (Teresko, 2007). However, this decision created a challenge to the design of the big fuselage, which is a multi-sectional cylindrical barrel covering the seating area of the aircraft. The new technology required more sections than previously used for aluminum-based fuselages. The result was that initial prototypes failed during the testing stage, forcing Boeing to redesign the body structure by adding more sections and scheduling more prototype testing, which added significantly to the schedule (Holmes, 2006).

The second technological change involved new kinds of avionics and computing systems that had never been used before on large commercial aircraft. They included the largest ever-used displays on any commercial aircraft (Ye et al., 2005), as well as replacing previous mechanical controls with electronic signal controls—a technology known as "Fly by Wire." Also new to commercial aircraft design, these technologies added to the project's delays by extending its wiring, installation, and integration processes (Holmes, 2006).

Boeing also adopted a new organizational paradigm for the development of Dreamliner and decided to outsource an unprecedented portion of the design, engineering, manufacturing, and production to a global network of 700 local and foreign suppliers (MacPherson & Pritchard, 2005). With more than 70% foreign development content, this decision turned Boeing's traditional supply chain into a *development chain* (Altfeld, 2010; Tang, Zimmerman, Nelson, & James, 2009). Tier-1 suppliers became responsible for the detailed design and manufacturing of 11 major subassemblies, while Boeing would only do system integration and final assembly. Figure 1 describes the project's major subassemblies and their tier-1 suppliers (Domke, 2008; Franck, Lewis, & Udis, 2009).

Furthermore, Boeing came up with a new risk and revenue sharing contract with its suppliers, called the "build-to-performance" model. According to the model, contract suppliers bear the non-recurring R&D cost up-front, own the intellectual property of their design, and get paid a share of the revenues from

[2]Please note that this article is based on publically available information and was not discussed or approved by Boeing.




Graphic research and design by David Badders, Seattle Post-Intelligencer. Sources: The Boeing Co., Vought Aircraft Industries Inc., GE Aviation, Rolls-Royce, Airbus, PPG Industries, Diehl Aerospace, Evergreen Aviation Technologies Corp. (EGAT)

**Figure 1:** 787 project's tier-1 suppliers.

future aircraft sales. Table 1 summarizes the main features of this model. Under the new model, the suppliers' roles are dramatically changed from mere subcontractors to strategic partners who have a long-term stake in the project. As we show later, however, this model created some risks, which caused extensive integration problems and additional delays.

Finally, Boeing employed a new assembly method. Subcontractors were required to integrate their own subsystems and send their preassembled subsystems to a single final assembly site. The goal was to reduce Boeing's integration effort by leveraging subcontractors to do more work compared with previous projects. However, many of these subcontractors were not able to meet their delivery schedules due to lack of experience in subsystem design and integration, as well as insufficient guidelines and training. As a consequence, parts and assemblies, which were sent to Boeing for integration, were missing the appropriate documentation, including instructions for final assembly.

## Comparing the Project's Events to the Original Plan

The original plan of the 787 was to have all subassemblies completed and delivered by June 2007, have the maiden flight in August 2007, and make the first delivery by May 2008. On July 8, 2007, a rollout ceremony was held for the first Dreamliner (Norris & Wagner, 2009). However, the aircraft's major systems had not yet been installed, and many parts were only attached with temporary fasteners (Trimble, 2007). It was the first of several delays prior to the first test flight, which took place nearly a year and a half later than planned (Cohan, 2009; Kotha & Srikanth, 2013). With more than 60 canceled orders, Boeing had to pay its customers nearly US$1 billion in penalties for late delivery because the first aircraft were not sellable. See Table 2 for a detailed sequence of events (*The Seattle Times*, 2009).

### *Project Development Difficulties*

Design issues were not the only causes of delays. Boeing listed addi-

| Scope | Contractual Arrangement/Responsibility |
|---|---|
| System design and architecture | Boeing as main contractor |
| Detailed part design | Suppliers |
| Interface design | Boeing defines interfaces; suppliers provide detailed designs, and Boeing serves as referee |
| Selecting and managing tier-2 suppliers | Tier-1 suppliers |
| Intellectual property | Owned by suppliers |
| Non-recurring development costs | Amortized costs paid by suppliers from 787 revenue |
| Time of payments to suppliers | When 787 is certified and delivered to customers |

**Table 1:** Boeing 787's build-to-performance model.

| Year | Month | Events |
|---|---|---|
| 2002 | December | Responding to airlines' calls for more fuel efficiency rather than extra speed, Boeing drops its "Sonic Cruiser" concept. Much of the Sonic Cruiser's composite materials, avionics, and engine technology will reappear in the 787 |
| 2003 | December | Everett, Washington, USA is chosen as the first assembly plant |
| 2004 | July | ANA places a 50-plane order |
| 2005 | September | Main features of the 787 airplane design are complete and detailed design work is sent to Boeing's global partners |
| | December | 288 orders by the end of 2005 |
| 2007 | June | A 0.3-inch gap was found at the joint between the nose-cockpit section and fuselage section, made by different suppliers. Engineers fixed it by disconnecting and reconnecting internal parts |
| | July | The first assembled 787 is rolled out at Everett, but unknown to the audience, it is a hollow shell |
| | September | **First delay**: three months. Due to shortage of fasteners and incomplete software |
| | October | **Second delay**: six months for first deliveries, three months for test flight. Due to unfinished work passed along by global partners and delays in finalizing the flight control software. Mike Bair, 787 program head, is replaced by Pat Shanahan |
| | December | 346 orders by the end of 2007 |
| 2008 | January | **Third delay**: three months for test flight. Due to unnamed suppliers and slow assembly progress at the Everett plant |
| | April | **Fourth delay**: six months, again for test flight; total of 15 months behind the original schedule for first deliveries. Due to continuing problems with unfinished work from suppliers |
| | September | A second machinists' strike begins at Boeing, lasting 57 days. The company struggles for a month afterward to get production back on track |
| | November | News emerges of a new, embarrassing and serious problem. About 3% of the fasteners put into the five test airplanes under construction in Everett were installed incorrectly and had to be removed and reinstalled |
| | December | **Fifth delay**: six months. Shanahan is put in charge of commercial-airplane programs, and Scott Fancher takes day-to-day operations lead on the 787 project. More than 900 orders by the end of 2008 |
| 2009 | January–February | Middle East leasing company LCAL and Russian airline S7 group cancel 37 orders |
| | June | **Sixth delay**: test flight is postponed indefinitely. Due to a structural flaw at the wing-body joint |
| | | Australian carrier Qantas cancels 15 orders |
| | | Boeing writes off US$2.5 billion because the first three planes are unsellable and suitable only for flight tests |
| | July | Boeing announces that it will acquire the 787 rear fuselage assembly plant in Charleston, South Carolina, USA, buying out its partner Vought for about US$1 billion |
| | October | Additional 10 orders canceled. The total number of order reduces to 840 |
| | | Intensive talks between Boeing and the machinists' union end in acrimonious failure. Boeing announces the choice of Charleston, South Carolina, USA, as the second final assembly plant |
| | November | Boeing mechanics complete the wing-body joint fix. Engineers repeat the wing stress test, and the Dreamliner gets the green light to fly |
| 2010 | August | **Seventh delay**: Boeing delays delivery of the first aircraft by three months due to engine failure and availability issues |
| | November | Boeing halts Dreamliner tests after an onboard fire |
| | December | **Eighth delay**: Boeing delays delivery **indefinitely**—no delivery date given |
| 2011 | September | First aircraft is delivered (40 months total delay) |
| 2013 | January | Entire 787 fleet in service is grounded for months by the FAA due to battery problems |

**Table 2:** 787 Dreamliner's sequence of main events.

tional reasons such as weight control, fastener shortages, incorrect installation, extensive delays in suppliers' work, and software development difficulties (McInnes, 2008). Following is a more detailed account of these reasons.

Fuselage design changes required altering joints between sections, as well as a strengthening wing design, resulting in an 8-ton increase in maximal takeoff weight. Boeing addressed this problem by additional and originally

unplanned redesign cycles, exploring multiple weight savings, which saved nearly 2 tons. (Domke, 2008).

In addition, the project repeatedly experienced insufficient supplies of basic components, such as fasteners, frames, clips, brackets, and floor beams. The body design changes required a different sleeve fastener design on wings, leading to the delay of the first test flight of August 2007. With 60 weeks of production lead time, the main fastener supplier, Alcoa Inc., was unable to meet demand on time (Lunsford & Glader, 2007). Furthermore, some fasteners were incorrectly installed (Gates, 2008).

But perhaps the most troubling issue in the Dreamliner project was the inability of Boeing's suppliers to meet the project's demands. This resulted in "traveled work," where suppliers' work was passed along back to Boeing's Final Assembly Line (FAL). As Pat Shanahan, the second project director, put it: "*We designed our factory to be a lean operation. And the tools and the processes, the flow of materials, the skills of personnel are all tailored to perform last-stage high-level integration, check out and test. We thought we could modify that production system and accommodate the traveled work from our suppliers, and we were wrong*" (Komonews.com, 2015).

### *How Did Boeing Deal With Its Unexpected Challenges and Delays?*

Faced with major delays due to redesigns, part shortages, incorrect installations, software delays, and even a union strike, Boeing initiated several bold actions to deal with these issues. Such actions eventually led to the introduction of what proved later to be a highly desired aircraft.

- In December 2008, Boeing opened a Production Operation Center in its Everett plant to better coordinate with its tier-1, as well as tier-2 and tier-3 suppliers. The Center's mission was to "monitor global production among suppliers, solve problems quickly and keep the program advancing" (James, 2009).
- Dreamliner's components and modules began testing right away at the original manufacturer's site before being shipped out to the next assembler. This way, Boeing was able to identify and solve problems when they occurred, rather than later, when their impact was detected.
- Since Vought turned out to be one of its least reliable suppliers, in 2009 Boeing decided to acquire Vought's interest in Global Aeronautica, and its operations in South Carolina for US$580 million.

## An Innovation and Contingency Perspective on Complex Projects

A retrospective look at the project's challenges, suggests that most of them were rooted in the company's decisions to engage new (or innovative) techniques and practices often used for the first time. While strategically justified, it seems that the company needed better adaptation of organizational and development practices to the innovation introduced by these decisions.

Innovation can be viewed as the "application of better solutions that meet new requirements, in-articulated needs, or existing market needs" (Frankelius, 2009). The Organisation for Economic Co-operation and Development (OECD) (2005) defines innovation from an overall broad perspective as "the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations" (OECD, 2005, p. 46). Complexity, in turn, in most studies is related to a large number of distinct and independent elements (Williams, 1999). Following these definitions, it is conceivable that Boeing's challenges were a result of a combination of multiple innovations in its Dreamliner development project. Thus, in the following discussion we describe the relevant literature on innovation and project management, which will be used for analyzing Boeing's experience and explaining the challenge of innovation posed by this project. We then use this analysis to depict possible alternative ways to manage such kinds of highly complex innovations.

### *As the Theory Suggests, One Size Does Not Fit All Innovations*

One of the early studies of innovation conducted by Marquis (1969) was dedicated to exploring the differences between two types of innovation: *incremental* (a small change in an existing product) and *radical innovation* (a change based on a completely new idea). This distinction appears often in many studies (e.g., Baker & Sinkula, 2007; Balachandra & Friar, 1997; Chao & Kavadias, 2008; Gemünden, Salomo, & Hölzle, 2007; Germain, 1996; Kock, Gemünden, Salomo, & Schultz, 2011; Leifer et al., 2000). Marquis (1969) also mentioned a third type, *system innovation*, which relates to large complex efforts (systems) that combine many new and/or improved ideas in one big system development project, such as aircraft, communication networks, or space programs; however, he did not investigate this kind of innovation in detail in his study. The concepts of *exploitation* versus *exploration* emerged later (March, 1991), essentially distinguishing between two types of learning: *improvements* or *modifications of existing ideas* and *introduction of fundamentally new ideas* (Benner & Tushman, 2003; Danneels, 2002; Gatignon, Tushman, Smith, & Anderson, 2002). Innovation studies have also expanded in additional directions, such as new product development (Chen, 2015; Salomo, Weise, & Gemünden, 2007), open innovation (Chesbrough, 2006; Gemünden et al., 2007), portfolio management (Beringer, Jonas, & Gemünden, 2012; Kock, Heising, & Gemünden, 2014; Unger, Rank, & Gemünden, 2014), or other industries such as automotive (Lenfle & Midler, 2009).

Another well-established and relevant concept is structural organizational

contingency theory, which suggests that organizations must find the right *fit* between problem and context and must adapt their structure, processes, and practices to the unique environment of their task. This idea implies that different kinds of organizations functioning in distinct environments must be structured and managed in different ways (Benner & Tushman, 2003; Burns & Stalker, 1961; De Brentani & Kleinschmidt, 2015; Drazin & Van de Ven, 1985; Hanisch & Wald, 2012; Howell, Windahl, & Seidel, 2010; O'Connor, 2008; Pennings, 1992; Ritter & Gemünden, 2003). Scholars have often suggested that organizations that perform more innovative tasks would be different from organizations which develop more routine products (e.g., Abernathy & Utterback, 1978; Burgelman, 1983; Dewar & Dutton, 1986; Drazin & Van de Ven, 1985; Galbraith, 1982; Perrow, 1967; Thompson, 1967).

Correlations between structural and environmental attributes have been well studied when the organization is the unit of analysis. However, they have only entered the realm of project management in the last two decades. The argument was that projects can be seen as "temporary organizations *within* organizations" and thus may exhibit variations in structure based on context and environment (Lenfle, 2008; Lundin & Söderholm, 1995; O'Connor & Rice, 2013; Payne & Turner, 1999; Shenhar, 2001).

The evolution of project management contingency theory and its relation to innovation was characterized by the introduction of specific context factors, which would distinguish projects by different dimensions, leading to specific contingency decisions (Hanisch & Wald, 2012). For example, Henderson and Clark (1990) have used a 2 × 2 matrix to distinguish between the components of a product and the ways they are integrated. Wheelwright and Clark (1992) have classified projects based on product and process types; Turner and Cochrane (1993) have grouped projects based on how well their goals and their means are defined; Youker (2002) has grouped projects based on product type; and Pich, Loch, and De Meyer (2002) have used a project's information adequacy (or level of uncertainty) to distinguish between three strategies: instructionism, learning, and selectionism. Shenhar and Dvir (2004, 2007) have used four dimensions to distinguish among projects: novelty, technology, complexity, and pace, and have shown how this categorization can be applied to innovation as well. It is interesting to note that the connection between projects and innovation is getting more and more attention recently, as demonstrated first in the 2007 IRNOP conference dedicated to this link (Brady & Söderlund, 2008). Consecutive articles discuss various aspects of innovation and project portfolio management. For example, Killen, Hunt, and Kleinschmidt (2008) studied Australian companies and found that project portfolio management practices are very similar for new service and tangible product development project portfolios. Biedenbach and Müller (2012) studied the relationship of innovative capabilities and long-term project success, whereas Sicotte, Drouin, and Delerue (2014) suggested a set of six critical capabilities for innovative companies managing successful projects. Unger et al., (2014) reported that corporate innovation culture and national-level culture are related to dimensions of project portfolio success, and Meifort (2015) reviewed the current research on innovation portfolio management and categorized it into four perspectives: optimization, strategy, decision making, and organization. The topics of complexity and uncertainty in projects have been often used interchangeably. For example, Geraldi, Maylor, and Williams (2011), when analyzing 25 notable papers, have referred to "complexity in projects" versus "complexity of projects" by suggesting an umbrella typology of five different dimensions of complexity: structural, uncertainty, dynamics, pace, and sociopolitical. In contrast, Howell et al. (2010) have presented uncertainty as the most common theme in the study of project contingency theory (PCT), followed by complexity, team empowerment, criticality, and urgency, whereas Bosch-Rekveldt, Jongkind, Mooi, Bakker, and Verbraeck (2011) have demonstrated the elements that contributed to project complexity by introducing the technical, organizational, and environmental (TOE) framework of complexities.

Based on these and other studies, four current conclusions about the state of knowledge of PCT emerge. First, just as for sustained organizations, "*there is no one best way*" for projects as well, and "*one size does not fit all*." Second, no generally accepted framework has emerged thus far to support the analysis of highly complex and innovative projects. Third, most emergent frameworks are theoretical or literature-based, with only a few grounded by empirical evidence. Fourth, research often offers limited prescriptive ideas on actually managing innovations. However, as claimed, "for practitioners a project's complexities can be used as a starting point for a reflection on the challenges a project faces, or will face, and the development of strategies to cope with them" (Geraldi et al., 2011, p. 983).

## Analysis

### *Could Contingency Methods Help Prepare Boeing for Its Challenges?*

As we have seen, Boeing's difficulties were a result of the following major challenges: The use of newly developed technologies, outsourcing a large extent of design to numerous, less experienced subcontractors (and creating a development chain), a new business model of revenue sharing, and a new assembly model. As claimed earlier, these strategies probably helped retaining Boeing's competitive positioning by taking advantage of modern technologies, and practices, but their execution was less than optimal.

In reviewing the current state of knowledge, no single available

framework seems comprehensive enough for analyzing the spectrum of innovation challenges in a highly complex project such as the Dreamliner. To enrich the analysis, and complement possible limitations in any single model, we combined three frameworks offered by different authors: Pich et al. (2002), Shenhar and Dvir (2004, 2007), and Geraldi et al. (2011), thus creating a broader perspective. We selected these frameworks based on the following criteria: the framework must offer practical implications for project innovation teams; it was based on empirical evidence, not just theory; or it adds a factor that is not covered by other models. The following section describes each model in detail and its accompanying discussion outlines the lessons that could be derived for Boeing's project. In a later section we combine all these lessons into one integrated overview.

### *Pich et al.'s Categories of Project Learning*

Pich et al. (2002) characterize projects based on the degree of information available upfront to the project teams. Each of their recommended three types of projects requires a different project management strategy as described below:

- **Instructionist project** is a project where most of the information needed for planning is available, and the project team has a good understanding of the "best policy" that has to be implemented. Planning an instructionist project mainly involves optimization that is focused on the critical path and risk management. The instructionist project primarily exploits known information and does not need to deal with high levels of uncertainty.
- **Selectionist project** is a project where there is not enough information to define an optimal policy; the project team is faced with a higher level of uncertainty, and it cannot accurately anticipate the results of its actions. Rather than exploit existing knowledge, the team is encouraged to explore; plan multiple trials and prototypes, while executing them simultaneously; and then select the best performing solution. From this point on, the project could be managed as an instructionist project.
- **Learning project** is a project susceptible to unforeseen events that might influence its course. In this environment, there is little benefit in detailed planning of the entire project, because the unforeseen might alter its course and force the team to learn and continuously readjust the plan. While each project needs a clear vision, its detailed planning can only be done for the nearest tasks and must be updated with progress.

In the Boeing case, the technologies of composite materials and "fly by wire" were new to this family of company products and this required an upfront analysis of the level of uncertainty and the allocation of sufficient time for testing and redesign. Similarly, the extensive outsourcing of design for the first time, as well as the new business model, required a slower pace of adaptation and learning of the new practices by all factors. However, Boeing employed what looks like an instructionist strategy (Pich et al., 2002), which is based on a low level of upfront uncertainty, such as construction, where activities, time, and cost are essentially predictable, and no surprises are expected. It does seem, however, that this project would require a selectionist style of project management. Such a style would ensure that the project is ready to acknowledge its upfront level of uncertainty and allocate sufficient resources for repetitive designs, prototype building, and testing before the final design is selected. It would also ensure enough time for training and certifying the project's subcontractors as well as adjusting the newly implemented business model.

### *Shenhar and Dvir's Diamond of Innovation*

The Dreamliner's project innovative challenges could also be analyzed by using the "Diamond of Innovation" model. Based on a study of over 600 projects, the "Diamond of Innovation" provides a framework for project classification (Shenhar & Dvir, 2004, 2007). Each one of its dimensions of *novelty*, *technology*, *complexity*, and *pace* consists of four possible project categories, and by selecting a category in each dimension, one creates a specific diamond-shaped view for each project, which serves as a project classifier. Once a classification is selected, the model helps identify the unique impact of each dimension, and provides recommendations for a preferred style of management. The Diamond of Innovation dimensions and their impact on a project are summarized in Table 3.

Using the Diamond of Innovation implies that the Dreamliner project could be classified as outlined below. (We then discuss the fit between the actual management and the required style based on this classification):

- **Novelty**: From its customers' perspective, the Dreamliner was a generational change in an existing line of previous commercial aircraft built by Boeing. That would place it at the *Platform* level of novelty, which really did not create a unique challenge to the company that made all the strategic decisions needed for a new platform. However, there was another challenging aspect of novelty. The new "build-to-performance" business model, however, was unfamiliar to the company and its subcontractors. As major stakeholders, they can be considered as "users," and for them it was an unknown experience. That challenge would move the novelty to a "*new-to-the-market*" level, which suggests that the implementation of the new model would require pilot testing and repetitive model modifications until the final version was established and fully understood.
- **Technology**: The technology of composite materials was new to the commercial aircraft industry, and no prior experience existed on how to design

| | |
|---|---|
| **Novelty:** Market Innovation—how new is the product to the market, users, and customers. Novelty level impacts market-related activities and the time and effort needed to define and freeze requirements (a higher novelty would delay this freeze) | • *Derivative:* Improvement in an existing product (e.g., a new color option in an MP3 player, the addition of a search feature in a software program)<br>• *Platform:* A new generation on an existing product line (e.g., new automobile model, new commercial airplane)<br>• *New-to-the-market:* Adapting a product from one market to another (e.g., first PC, consumer's microwave oven)<br>• *New-to-the-world:* A product that no one has seen before (e.g., the first Post-it note) |
| **Technology:** Technological Innovation—how much new technology is used. It impacts product design, development, testing, and the requisite technical skills (a higher technology level requires additional design cycles and results in a later design freeze) | • *Low-tech*: No new technology is used (e.g., house, city street)<br>• *Medium-tech*: Some new technology (e.g., automobile, appliances)<br>• *High-tech*: All or mostly new, but existing technologies (e.g., satellite, fighter jet)<br>• *Super high-tech:* Critical technologies do not exist (e.g., Apollo moon landing) |
| **Complexity:** Level of System Innovation—represented by the complexity of the product or the organization. Complexity impacts the degree of formality and coordination needed to effectively manage the project | • *Component/Material:* The product is a discrete component within a larger product, or a material<br>• *Assembly:* Subsystem performing a single function (e.g., CD player, cordless phone)<br>• *System:* Collection of subsystems, multiple functions (e.g., aircraft, car, computer)<br>• *Array:* Widely dispersed collection of systems with a common mission (e.g., city transit system, air traffic control, Internet) |
| **Pace:** Urgency of the Innovation—How critical is your time frame. It impacts the time management and autonomy of the project management team | • *Regular:* Delays are not critical (e.g., community center)<br>• *Fast-competitive:* Time to market is important for the business (e.g., satellite radio, plasma television)<br>• *Time-critical:* Completion time is crucial for success by exploiting a window of opportunity (e.g., mission to Mars, Y2K)<br>• *Blitz:* Crisis project—immediate solution is necessary (e.g., Apollo 13, September 11) |

**Table 3:** Diamond of Innovation: definitions, dimensions, and project types.

and integrate it into a large wide body such as the 787. Similarly, the technologies of electronic controls ("fly by wire") were also new in the commercial aircraft sector. The innovative use of these technologies placed the Dreamliner in the *high-tech* category of innovation. In contrast, previous commercial aircraft such as the 777, which had used traditional aluminum body materials, would be classified as *medium-tech*. The ramifications of such innovative technologies suggest that this project required a different approach than that used in Boeing's previous generations. The immature technologies required additional time, more testing, and additional design-build-test cycles, as well as more prototyping. Such additional work was not planned in advance, requiring elaborate decision-making processes, and additional design resources (which were later added to the program).

- **Complexity**: Typically, most aircraft-building efforts can be considered *systems* on the dimension of complexity. The Dreamliner project, however, added a significant amount of complexity to the effort. Management's decision to outsource an unprecedented amount of design and development work to hundreds of subcontractors worldwide required an enormous amount of coordination and clear rules in work procedures as well as documentation. We propose that such complexity pushed the program from the *system* level to the *array* category, which requires extensive coordination and formality. The ramifications for the project were significant. What appears to be missing in this case was a detailed and elaborate system of vendor education, training, and verification that these vendors can actually do the job. In addition, Boeing had to invest in a highly formal and strict policy for vendor behavior, standards of work, and coordination. Preparing these formal rules and procedures required an extensive investment of time for building the complex management and control system. Array projects are often conducted across national borders and cultures, requiring them to find specific ways to overcome language and cultural differences. It seems that Dreamliner needed to implement more of these efforts upfront.
- **Pace**: The Dreamliner project was expected to be in the market in time to face and benefit from the growing demand. That would rank this project at the *fast competitive* level. Indeed, Boeing intended to treat the project as fast competitive, but faced with unexpected delays, the pace often seemed even faster.

Based on these observations, we classify the Dreamliner project as a *platform/new-to-the-market*, *high-tech*, *array*, and *fast competitive*, leading to a specific style of management for this classification. However, a careful analysis of the program's actual style was different along the dimensions of technology and complexity. Specifically, the actual approach chosen for managing novelty was closer to *platform*, instead

of *new-to-the-market*, *medium-tech* approach, instead of *high-tech*, and the one chosen to manage complexity was closer to the category of *system* rather than *array*. Figure 2 is a visual depiction of the gaps between the required management style (bold diamond) and its actual counterpart (dashed).

***Geraldi et al.'s Typology of Complexity***

Based on an extensive literature survey, Geraldi et al. (2011) have adopted a broad perspective to the idea of complexity, and thus identified five dimensions of a project's complexity: structural complexity, uncertainty, dynamics, pace, and socio-political complexity. Two of them—dynamics and socio-political complexity—were not covered by the frameworks used earlier and may add new insights to the analysis.

- **Structural complexity**: Structural complexity relates to a large number of distinct and interdependent elements. It is impacted by size, variety, and interdependence of the elements.
- **Uncertainty**: Uncertainty represents the gaps between the amount of information required to make a decision and what is available. Uncertainty has an intrinsic relationship with risks, but as the literature suggests, there may be different kinds of uncertainty, such as uncertainty of goals and uncertainty of methods (Turner & Cochrane, 1993).
- **Dynamics**: Dynamics refers to changes in factors as goals or specifications. When changes are not well communicated or assimilated by the team, such changes may lead to high levels of disorder, rework, or inefficiency. Projects may not only change "outside-in" but also "inside-out," where teams may change their constitution or motivation, or internal politics may take over.
- **Pace**: Pace relates to the temporal aspects of a project. It represents the urgency and criticality of time goals. Pace essentially refers to the rate or speed at which produces should be delivered.
- **Socio-political complexity**: This kind of complexity relates to the problems involved when managing stakeholders, such as lack of commitment, or problematic relationships between stakeholders, as well as those related to the team. Issues that are often mentioned in this category include "complexity of interaction" between people and organizations, and differences of languages, cultures, and disciplines. It also refers to the complexity of the problem situation itself and the complexity of the human and/or group factor. Overall, this factor emerges as a combination of the political aspects and emotional aspects involved in projects.

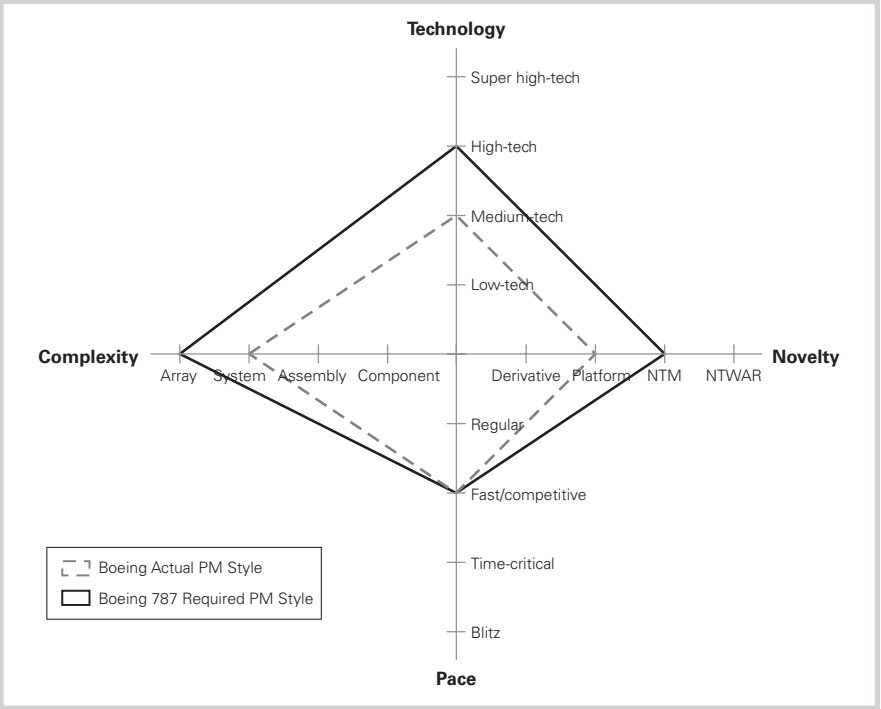



**Figure 2:** 787 project's Diamond of Innovation.

Geraldi et al. (2011) do not discuss specific impacts of each complexity dimension on project management, but rather, indicate that the assessment of project complexity could affect such items as the choices of competitive priorities, different project management methodologies and tools, managerial capacity development, or identifying problems in troubled projects. Furthermore, they note that the assessment of the type of complexity in projects is often subjective and will be influenced by the project manager.

Perhaps the most significant contribution of Geraldi et al.'s work (2011) is the proposition that complexity dimensions are frequently interdependent. For example, they indicate that high uncertainty may increase the level of dynamic complexity, which will bring increased structural complexity. Similarly, high structural complexity may lead to increased socio-political complexity, and high socio-political complexity may lead to increased levels of change and uncertainty. These interdependencies are clearly noticeable in the case of Dreamliner, and are outlined in the following discussion.

Geraldi et al.'s model (2011) may offer further insights into the analysis of Boeing's Dreamliner challenges, particularly with regard to the dynamics and socio-political complexity dimensions. The significant number of changes that were required in order to get the project back on track increased the degree of

the dynamics compared to the original intentions. These dynamics required continuous adjustments of the project's organizational structure, design, and testing processes, additional resources and modified processes, not to speak of the added resources. They also caused several changes in leadership during the development period. Once again, one may claim that, had the company originally assessed the degree of innovation in technology and complexity, the original plan might have been more realistic and thus may have avoided much of the unplanned dynamics.

The last dimension of socio-political complexity is also meaningful. Boeing's intentions of outsourcing design to a large network of subcontractors and the new "build-to-performance" incentives model created a high level of additional complexity. Subcontractors had difficulties adjusting to Boeing's advanced design requirements, which were augmented by geographical distances, language, and cultural differences. In retrospect, analysis of Geraldi et al.'s model suggests that the project should have been better prepared for these kinds of complexities, which resulted from its business-related decisions. Such preparations would require an intense process of subcontractors' education about Boeing's requirements and design standards, followed by a tight system of coaching, reviewing, controlling, and on-going communication with its subcontractors.

### *Combined Lessons from the Three Models*

As we have seen, analyzing the Dreamliner project using different innovation models may help explain the company's difficulties and suggest alternative ways that could have prevented some or all of these delays. Overall, a careful upfront analysis of the project during the planning process would look for all the new practices that distinguish this project from its predecessors, and select the mitigation techniques that would deal with these challenges upfront. Table 4 summarizes the combined lesson that we derived from our analysis, along with possible alternative activities that might have prevented the difficulties.

A combined analysis using all three models offers a more in-depth understanding of the project's challenges than using one model alone. Specifically, we discuss these combined insights using the two major perspectives of uncertainty and complexity, as well as their interdependencies. First, Pich's et al. (2002) model shows that the project adopted an instructionist strategy, which is based on relatively low levels of uncertainty, instead of the selectionist strategy that is typically required in cases that involve a higher level of uncertainty. Shenhar and Dvir's model (2007) analysis confirms this observation, by making a distinction between two types of uncertainty—novelty and technology. In terms of novelty, Boeing treated the uncertainty faced by its stakeholders (subcontractors) as "platform," where in most cases the experience of a previous generation is essentially repeated. However, in this case, for Boeing's stakeholders, the design and development experience was new and its novelty in our opinion should be considered as "new-to-the-market." Similarly, by introducing several key new technologies, Boeing has apparently lifted technological uncertainty from a "medium-tech" to a "high-tech" level; its managerial practices, however, were in our judgment, more typical of a "medium-tech" level.

From the complexity standpoint, we may conclude that the project's complexity was higher than it was in Boeing's previous generations due to the decision to share the design work with an extensive number of subcontractors. Shenhar and Dvir's (2007) model would suggest that this project should thus be seen as an "array"; however, our observation suggests that its actual management practices fit better with the "system" level, where everything is done in one location and in one organization. In reality, we believe that the integration and communication needed for this extensive worldwide effort suggests that this project should have been treated as an "array." Geraldi et al.'s two dimensions of complexity dynamics and socio-political complexity only strengthen this analysis (2011). Based on our observation, Boeing treated the project as having a low level of dynamics and socio-political complexity, as if things are quite stable and the cultural environment is mostly homogeneous. However, the need to make an extensive number of changes during the development and communicate them with a large collection of subcontractors around the world, have increased, in our view, both the dynamics and the socio-political complexities from low to high.

Finally, Geraldi et al.'s interdependencies of dimensions are also seen in the other two models. When an instructionist strategy (Pich et al., 2002) is replaced by a selectionistic strategy, or when novelty or technology shift from platform and medium-tech to new-to-the-market and high-tech, both the dynamic and socio-political uncertainties advance from the low to the high levels. A similar argument holds true for the shift from system to array in Shenhar and Dvir's model (2007). In sum, as one can see, each model offers a slightly different analytical perspective, but collectively, we believe, the multi-model analysis indeed enriches our understanding of the project's challenges and potential lessons.

## Discussion

Boeing's confidence in its past experience and record of success perhaps led project leaders to believe that the new project would be as successful as before. Based on the above analysis, however, we demonstrated that the challenges and scope of innovation were probably underestimated. The level of new practices required to manage design subcontractors and the extent of technological innovation were much higher than in its previous commercial aircraft projects. The effort involved in integrating new technologies required a much

| Model Used for Analysis | Variable | Actually Used | Recommended | Implications and Discussion |
|---|---|---|---|---|
| **Pich et al., (2002)** | **Project management learning strategy** | Instructionist strategy is used for a project where most of the information for planning exists and there is a low level of uncertainty | Selectionist strategy is used where there is insufficient information for planning, due to high level of uncertainty | Faced with extensive levels of uncertainty, the project had to create a master plan with additional prototypes and tests before final decisions could be made. This would probably extend the original schedule, but eventually produce a more realistic plan that would reduce the final cost |
| **Shenhar and Dvir (2007)** | **Novelty**: Market or User (Stakeholder) Uncertainty | Platform—A next generation in an existing line of products | Platform and New to the Market—To customers, the product was indeed a Platform. But for subcontractors, Boeing's design and incentives model were "New to the Market" | The company had to train and coach subcontractors in its design methods as they learned to address new design and development practices. In addition, the new incentives model was rarely used in the industry and was new to Boeing's overseas partners. The model had to be carefully implemented with small pilots where both sides experience it and gradually learn how to work effectively with it |
| | **Technology**: Extent of using new technology—level of technological uncertainty | Medium-tech—where most technologies are well known with a small number of changes | High-tech—the project is using new technology that was recently developed and rarely used before in such kinds of projects | The high-tech level required planning at least three to five design cycles, and an increased number of prototypes that would enable testing the new technologies design and integrate it with the entire aircraft |
| | **Complexity**: How complex is the product and/or the organization that is creating it | System—a collection of subsystems that is creating a multifunctional product | Array (System of Systems)—a large collection of systems or organizations, working together for a common mission, often widely dispersed geographically | Boeing's development chain created an array of companies around the world that was engaged in design and development. To succeed, such an array must be carefully coordinated with clear rules, standards, and common forms of documentation, reporting, and communication. These elements are typically prepared before the array is launched worldwide |
| **Geraldi et al., (2011)** | **Dynamics—** Extent of changes | Low Dynamics—not too many changes are expected and the process is executed as planned | High Dynamics—where many changes are common and continuous adjustments are needed | The high levels of uncertainty led to numerous changes, which increased the dynamics level of the project |
| | **Socio-political Complexity—** Complexity due to sociological differences and political influences | Low level of socio-political complexity, as in previous projects where most of the work was done inside | High level of socio-political complexity, which resulted from the need to coordinate the large collection of different cultures and languages | The resulting high socio-political complexity required extensive attention to the cultural and languages differences. The company had to prepare an extensive training program to make all managers aware of these differences and teach them strategies to cope with them |

**Table 4:** Dreamliner's innovation challenges analysis.

higher allocation of time and other resources than originally planned. Lacking an established framework for such allocations, planners found out later that they needed to add more design cycles to the original plan, build more prototypes, and conduct additional testing. Later corrective actions led to delays and higher cost, which may have been avoided had these challenges been addressed in advance.

In addition, from an organizational standpoint, the development effort of the Dreamliner was more complex than in previous projects due to the innovation involved in outsourcing much of the design and development, as well as a new incentives model. The project lacked sufficient organizational support systems for managing the new and highly complex network of inexperienced suppliers. Here, too, such systems were eventually put in place, but at a much higher cost than if implemented at inception. The interface between technological innovation and organizational complexity was also significant. The time required for integration and for redesign iterations *across* multiple firms was underestimated. Boeing originally allocated only two months for system integration before scheduling the first flight. In retrospect, that time was much lower than needed.

Similarly, from a strategic standpoint, we believe that the company was not fully ready to manage the innovative business model of Build-to-Performance. Such innovation required the burden of fully controlling strategic outsourcing, supplier selection, contracting, monitoring, testing, and quality control, as well as addressing the cultural and distance differences; however, only a few of these activities were completed before the project was launched. Our analysis indicates that the company should have selected suppliers more carefully based on their R&D capabilities, level of commitment, and financial strength. Furthermore, drawing from the analysis, we believe that the company would have greatly benefited by initiating an extensive training program for its subcontractors, making sure they were ready to take on the challenge before they could commit to undertaking the design and development work.

Tactically, Boeing found it difficult to resolve the incentive issues underlying traveled work by linking suppliers' performance to suppliers' gain. The models may indicate that Boeing should have revised the risk-revenue sharing contract to provide mid-course financial incentives for suppliers to work faster and better, while penalizing them for delays and unnecessary traveled work. In addition, open communication and well-planned monitoring and controlling suppliers' processes could have effectively reduced traveled work, ensuring only properly completed work would pass on to the next stage, while helping detect problems early on.

### *What Can Companies and Researchers Learn From Boeing's Experience?*

Innovation is clearly one of the major drivers of economic growth; yet, it is risky and often ends up in disappointing results or failure. For example, Tepic, Kemp, Omta, and Fortuin (2013) reported 16 failures out of 38 innovation projects conducted by European industry companies and Baron, Esteban, Xue, Esteve, and Malbert (2015) discussed the cooperation between processes related to system development and project management in developing new products. Empirical innovation studies have often focused on small- or medium-sized projects that built tools, appliances, cars, or software; yet, as mentioned, highly innovative and complex projects have received less attention. Complex projects involve a substantial degree of difficulty due to a large number of components and technologies, involvement of numerous organizations, extensive communication and coordination requirements, and widely dispersed teams. When it comes to innovation, the challenge is even greater, leading to higher risk, which often requires adapting specific management processes during the development project. As Gann and Salter (2000), Hobday and Rush (1999), and Davies and Mackenzie (2012) indicated, the management of complex projects, which involve an integration of multiple components, calls for understanding and implementation of practices derived from the company strategy, management practices, and organizational processes. While the management of innovation in highly complex projects is still not fully investigated, most traditional project and program management tools rarely deal with planning and managing the project's innovation. Such models tend to assume that projects mostly are linear, certain, and predictable, and pretty much, "one size fits all." Well-established traditional risk management tools are aimed at protecting a project when things might fail, hence providing a preconceived remedy (or mitigation) when things are going wrong. Based on our assessment, we suggest that innovation management, however, is not about "what can go *wrong*?" It is about figuring out "how long will it take to get it *right*?"

## Conclusions

Our analysis has shown that highly complex and innovative projects may benefit from adopting a contingency approach for their planning and execution processes. One of the main lessons of this and similar contingency studies is that "*one size does not fit all innovations.*" Companies as well as researchers may explore more ways to understand the differences among projects and among different innovations. The three models for the analysis used in this article have demonstrated possible ways to identify such differences and adapt optimal management strategies. Pich et al.'s (2002) model shows how different levels of upfront information impact the project management strategy; for a best fit, they recommended selecting between the instructionist, selectionist, and learning strategies. The Diamond of Innovation (Shenhar & Dvir, 2004, 2007) provides a possible framework for analyzing innovation at the project level by integrating project management and innovation management. Classifying a project using the Diamond of Innovation dimensions, leads to specific decisions based on each dimension. For example, the model suggests that a high-tech project must include at least three cycles of design, build, and test. It also suggests that such projects need to allocate about 30% of the time and budget as contingent resources beyond a typical traditional plan. Similarly, an array program must prepare clear guidelines and coordinating mechanisms to make sure all components and participating companies are using the same terminology and standards, are similarly trained, and are effectively communicating. Geraldi et al.'s (2011) model specifically addresses five kinds of complexity, adding the dynamics and socio-political dimensions to previously existing models. Low or high levels in these dimensions require specific attention to their impact.

These models however, may not be the only ways to deal with innovation. For example, as early as 1984, Saren (1984) suggested classifying existing models of innovation according to five types: departmental-stage models, activity-stage models, decision-stage

models, conversion process models, and response models. More recently, Garcia and Calantone (2002) identified the constructs that are related to marketing and technological perspectives, at the macro and micro levels of a project. They presented a comprehensive list of constructs based on radicalness, newness, uniqueness, and complexity. Undoubtedly, additional models of innovation may be developed and applied to the fast-changing world of innovation.

A second clear conclusion we derived from our analysis is that there is currently no single comprehensive model to understand and analyze the entire spectrum of innovation challenges in highly complex projects such as the Dreamliner. After accepting the reality that one size does not fit all, practicing companies may still need to rely on a combination of models to understand the extent of innovation in a project and find the optimal ways of managing them. Furthermore, using several models of analysis may shed different lights on understanding the challenges of a complex project. Contingency aspects could be multifaceted and interactive, and no single or best model provides an overall direction or conclusive recommendations at this time. Different models may also be complementary to each other, and if used together, they may compensate for weaknesses or limitations of any single model alone.

This study may also offer new directions for further research. As we mentioned, research communities have typically focused on smaller scale projects. The more complex projects have received less attention thus far. There is clearly a need to develop comprehensive models of innovation in highly complex projects. Such models will establish a new basis for understanding the links between complexity, uncertainty, and innovation. We contend that future researchers may find ample opportunities for studying this important and intriguing field.

One of the main directions for future research is seeking additional and perhaps more refined models to distinguish among projects. Such distinctions may be of two kinds: First, identifying the major dimensions that characterize typical qualities of projects. For example, future researchers may find additional types of uncertainties and complexities in projects. The challenge would be to identify what really characterizes contingencies and how to avoid overlaps and contradictions. The second kind of investigation may be aimed at finding different scales or ranks for each dimension. Classical low-high distinctions seem to have been replaced in recent years by more refined frameworks involving three, four or more levels of distinction.

Once new dimensions and types are offered, another main direction for future studies is identifying managerial implications for different kinds of projects on each dimension. Such implications may relate to the organizational issues of complex projects. For example, should highly innovative projects be organized differently from lower innovative efforts? Differences may also be found in planning, monitoring, team selections, managerial qualities, subcontracting, stakeholder management, and many others.

Finally, this study is not free of limitations. First, using one case study is clearly insufficient to offer a comprehensive view of the industry or other complex innovative projects. Second, our research method, which relied on open sources, has a potential limitation of missing an in-depth better understanding of the project's internal dynamics and managerial processes taken by Boeing. Third, in this kind of study, one can only analyze the difficulties encountered during the project. It is impossible, however, to predict what may have happened if Boeing had taken a different approach. Thus, all potential remedies suggested at this stage can only be seen as possible options without a clear guarantee for better success. Finally, the lack of one comprehensive acceptable theory and the need to rely on a collection of models might have made this study prone to the specific choices of the researchers. Nevertheless, this study can be seen as a step forward toward a better understanding of the nature of innovation combined with complexity. From a research and theory perspective, this study has shown how theoretical models could offer real guidance to practicing organizations in addressing complex problems, particularly when using a combination of theories, rather than one model individually. More studies in the future may use this route to strengthen the link between theory and practice.

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MANAGEMENT SCIENCE
Vol. 32, No. 5, May 1986
*Printed in U.S.A.*

# CENTRAL PROBLEMS IN THE MANAGEMENT OF INNOVATION*

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Innovation is defined as the development and implementation of new ideas by people who over time engage in transactions with others within an institutional order. This definition focuses on four basic factors (new ideas, people, transactions, and institutional context). An understanding of how these factors are related leads to four basic problems confronting most general managers: (1) a human problem of managing attention, (2) a process problem in managing new ideas into good currency, (3) a structural problem of managing part-whole relationships, and (4) a strategic problem of institutional leadership. This paper discusses these four basic problems and concludes by suggesting how they fit together into an overall framework to guide longitudinal study of the management of innovation.
(ORGANIZATIONAL EFFECTIVENESS; INNOVATION)

## Introduction

Few issues are characterized by as much agreement as the role of innovation and entrepreneurship for social and economic development. Schumpeter's (1942) emphasis on the importance of innovation for the business firm and society as a whole is seldom disputed. In the wake of a decline in American productivity and obsolescence of its infrastructure has come the fundamental claim that America is losing its innovativeness. The need for understanding and managing innovation appears to be widespread. Witness, for example, the common call for stimulating innovation in popular books by Ouchi (1981), Pascale and Athos (1981), Peters and Waterman (1982), Kanter (1983), and Lawrence and Dyer (1983).

Of all the issues surfacing in meetings with over 30 chief executive officers of public and private firms during the past few years, the management of innovation was reported as their most central concern in managing their enterprises in the 1980's (Van de Ven 1982). This concern is reflected in a variety of questions the CEOs often raised.

1. How can a large organization develop and maintain a culture of innovation and entrepreneurship?
2. What are the critical factors in successfully launching new organizations, joint ventures with other firms, or innovative projects within large organizations over time?
3. How can a manager achieve balance between inexorable pressures for specialization and proliferation of tasks, and escalating costs of achieving coordination, cooperation, and resolving conflicts?

Given the scope of these questions raised by CEOs, it is surprising to find that research and scholarship on organizational innovation has been narrowly defined on the one hand, and technically oriented on the other. Most of it has focused on only one kind of organizational mode for innovation—such as internal organizational innovation (Normann 1979), or new business startups (e.g., Cooper 1979)—or one stage of the innovation process—such as the diffusion stage (Rogers, 1981)—or one type of innovation—such as technological innovation (Utterback 1974). While such research has provided many insights into specific aspects of innovation, the encom-

*Accepted by Arie Y. Lewin; received December 10, 1984. This paper has been with the author $3\frac{1}{2}$ months for 1 revision.



0025-1909/86/3205/0590$01.25

passing problems confronting general managers in managing innovation have been largely overlooked.

As their questions suggest, general managers deal with a set of problems that are different from and less well understood than functional managers. We concur with Lewin and Minton's (1985) call for a general management perspective on innovation—one that begins with key problems confronting general managers, and then examines the effects of how these problems are addressed on innovation effectiveness. The purpose of this paper is to present such a perspective on the management of innovation. Appreciating these problems and their consequences provides a first step in developing a research program on the management of innovation.

The process of innovation is defined as the development and implementation of new ideas by people who over time engage in transactions with others within an institutional context. This definition is sufficiently general to apply to a wide variety of technical, product, process, and administrative kinds of innovations. From a managerial viewpoint, to understand the process of innovation is to understand the factors that facilitate and inhibit the development of innovations. These factors include ideas, people, transactions, and context over time. Associated with each of these four factors are four central problems in the management of innovation which will be discussed in this paper.

First, there is *the human problem of managing attention* because people and their organizations are largely designed to focus on, harvest, and protect existing practices rather than pay attention to developing new ideas. The more successful an organization is the more difficult it is to trigger peoples' action thresholds to pay attention to new ideas, needs, and opportunities.

Second, *the process problem is managing ideas into good currency* so that innovative ideas are implemented and institutionalized. While the invention or conception of innovative ideas may be an individual activity, innovation (inventing and implementing new ideas) is a collective achievement of pushing and riding those ideas into good currency. The social and political dynamics of innovation become paramount as one addresses the energy and commitment that are needed among coalitions of interest groups to develop an innovation.

Third, there is *the structural problem of managing part-whole relationships*, which emerges from the proliferation of ideas, people and transactions as an innovation develops over time. A common characteristic of the innovation process is that multiple functions, resources, and disciplines are needed to transform an innovative idea into a concrete reality—so much so that individuals involved in individual transactions lose sight of the whole innovation effort. How does one put the whole into the parts?

Finally, the context of an innovation points to *the strategic problem of institutional leadership*. Innovations not only adapt to existing organizational and industrial arrangments, but they also transform the structure and practices of these environments. The strategic problem is one of creating an infrastructure that is conducive to innovation.

After clarifying our definition of innovation, this paper will elaborate on these four central problems in the management of innovation. We will conclude by suggesting how these four problems emerge over time and provide an overall framework to guide longitudinal study of innovation processes.

## Innovative Ideas

An Innovation is a new *idea*, which may be a recombination of old ideas, a scheme that challenges the present order, a formula, or a unique approach which is perceived as new by the individuals involved (Zaltman, Duncan, and Holbek 1973; Rogers

1982). As long as the idea is perceived as new to the people involved, it is an "innovation," even though it may appear to others to be an "imitation" of something that exists elsewhere.

Included in this definition are both technical innovations (new technologies, products, and services) and administrative innovations (new procedures, policies, and organizational forms). Daft and Becker (1979) and others have emphasized keeping technical and administrative innovations distinct. We believe that making such a distinction often results in a fragmented classification of the innovation process. Most innovations involve new technical and administrative components (Leavitt 1965). For example Ruttan and Hayami (1984) have shown that many technological innovations in agriculture and elsewhere could not have occurred without innovations in institutional and organizational arrangements. So also, the likely success of developments in decision support systems by management scientists largely hinges on an appreciation of the interdependence between technological hardware and software innovations on the one hand, and new theories of administrative choice behavior on the other. Learning to understand the close connection between technical and administrative dimensions of innovations is a key part of understanding the management of innovation.

Kimberly (1981) rightly points out that a positive bias pervades the study of innovation. Innovation is often viewed as a good thing because the new idea must be useful—profitable, constructive, or solve a problem. New ideas that are not perceived as useful are not normally called innovations; they are usually called mistakes. Objectively, of course, the usefulness of an idea can only be determined after the innovation process is completed and implemented. Moreover, while many new ideas are proposed in organizations, only a very few receive serious consideration and developmental effort (Wilson 1966; Maitland 1982). Since it is not possible to determine at the outset which new ideas are "innovations" or "mistakes," and since we assume that people prefer to invest their energies and careers on the former and not the latter, there is a need to explain (1) how and why certain innovative ideas gain good currency (i.e., are implemented), and (2) how and why people pay attention to only certain new ideas and ignore the rest. These two questions direct our focus to problems of managing ideas into good currency and the management of attention.

## The Management of Ideas

It is often said that an innovative idea without a champion gets nowhere. *People* develop, carry, react to, and modify ideas. People apply different skills, energy levels and frames of reference (interpretive schemas) to ideas as a result of their backgrounds, experiences, and activities that occupy their attention. *People become attached to ideas over time through a social-political process of pushing and riding their ideas into good currency*, much like Donald Schon (1971) describes for the emergence of public policies. Figure 1 illustrates the process.

Schon states that what characteristically precipitates change in public policy is a disruptive event which threatens the social system. Invention is an act of appreciation, which is a complex perceptual process that melds together judgments of reality and judgments of value. A new appreciation is made as a problem, or opportunity is recognized. Once appreciated, ideas gestating in peripheral areas begin to surface to the mainstream as a result of the efforts of people who supply the energy necessary to raise the ideas over the threshold of public consciousness. As these ideas surface networks of individuals and interest groups gravitate to and galvanize around the new ideas. They, in turn, exert their own influence on the ideas by further developing them and providing them with a catchy slogan that provides emotional meaning and energy to the idea.

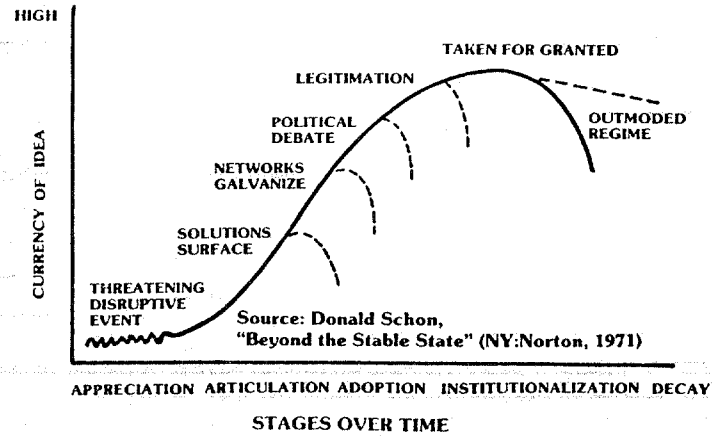


FIGURE 1. Managing Life Cycle of Ideas in Good Currency.

However, Schon indicates that ideas are not potent to change policy unless they become an issue for political debate and unless they are used to gain influence and resources. The debate turns not only on the merits of the ideas, but also on who is using the ideas as vehicles to gain power. As the ideas are taken up by people who are or have become powerful, the ideas gain legitimacy and power to change institutions. After this, the ideas that win out are implemented and become institutionalized—they become part of the conceptual structure of the social system and appear obvious, in retrospect. However, the idea remains institutionalized for only as long as it continues to address critical problems and as long as the regime remains in power.

Schon's description of the stages by which ideas come into good currency is instructive in its focus on the social-political dynamics of the innovation process. The description emphasizes the *centrality of ideas as the rallying point around which collective action mobilizes*—organizational structures emerge and are modified by these ideas. Moreover, it is the central focus on *ideas* that provides the vehicle for otherwise isolated, disconnected, or competitive individuals and stakeholders to come together and contribute their unique frames of reference to the innovation process. Schon (1971, p. 141) states that these stages characteristically describe the process features in the emergence of public policies "regardless of their content or conditions from which they spring." Analogous descriptions of this social-political process have been provided by Quinn (1980, especially p. 104) for the development of corporate strategies, and by March and Olsen (1976) for decision making in educational institutions.

However, there are also some basic limitations to the process that lead to inertia and premature abandonment of some ideas. First, there tends to be a short-term problem orientation in individuals and organizations, and a facade of demonstrating progress. This has the effect of inducing premature abandonment of ideas because even if problems are not being solved, the appearance of progress requires moving on to the next batch of problems. Thus, "old questions are not answered—they only go out of fashion' (Schon 1971, p. 142). Furthermore, given the inability to escape the interdependence of problems, old problems are relabeled as new problems. As a result, and as observed by Cohen, March and Olsen (1972), decision makers have the feeling they are always working on the same problems in somewhat different contexts, but mostly without results.

Except for its use in legislative bodies, the idea of formally managing the socio-political process of pushing and riding ideas into good currency is novel. However, as Huber (1984, p. 938) points out, the decision process is similar to project management and program planning situations. Thus, Huber proposes the adoption of proven

project management and program planning technologies (e.g., PERT, CPM and PPM) for managing the production of ideas into good currency. For example, based upon a test of the Program Planning Model, Van de Ven (1980a, b) concluded that the PPM avoids problems of decision flight and falling into a rut that are present in March and Olsen's (1976) garbage can model of anarchical decision making. This is accomplished by the PPM's three-way matching of phased tasks with different decision processes and with different participants over time in a program planning effort.

A second limitation of the process is that the inventory of ideas is seldom adequate for the situation. This may be because environmental scanning relevant to an issue does not uncover the values and partisan views held by all the relevant stakeholders. Gilbert and Freeman (1984) point out that with the general concept of environmental scanning, current models of strategic decision making gloss over the need to identify specific stakeholders to an issue and to examine their underlying values which provide reasons for their actions. Viewing the process from a game theoretic framework, they state that "effective strategy will be formulated and implemented if and only if each player successfully puts himself or herself in the place of other players and engages in trying to see the situation from the others' viewpoints" (Gilbert and Freeman 1984, p. 4).

A third, and even more basic problem is the management of attention—how do individuals become attached to and invest effort in the development of innovative ideas? Human beings and their organizations are mostly designed to focus on, harvest, and protect existing practices rather than to pave new directions. This is because people have basic physiological limitations of not being able to handle complexity, of unconsciously adapting to gradually changing conditions, of conforming to group and organizational norms, and of focusing on repetitive activities (Van de Ven and Hudson 1985). One of the key questions in the management of innovation then becomes how to trigger the action thresholds of individuals to appreciate and pay attention to new ideas, needs and opportunities.

## The Management of Attention

Much of the folklore and applied literature on the management of innovation has ignored the research by cognitive psychologists and social-psychologists about the limited capacity of human beings to handle complexity and maintain attention. As a consequence, one often gets the impression that inventors or innovators have super-human creative heuristics or abilities to "walk on water" (Van de Ven and Hudson 1985). *A more realistic view of innovation should begin with an appreciation of the physiological limitations of human beings to pay attention to nonroutine issues, and their corresponding inertial forces in organizational life.*

### *Physiological Limitations of Human Beings*

It is well established empirically that most individuals lack the capability and inclination to deal with complexity (Tversky and Kahneman 1974; Johnson 1983). Although there are great individual differences, most people have very short spans of attention—the average person can retain raw data in short-term memory for only a few seconds. Memory, it turns out, requires relying on "old friends," which Simon (1947) describes as a process of linking raw data with pre-existing schemas and world views that an individual has stored in long-term memory. Most individuals are also very efficient processors of routine tasks. They do not concentrate on repetitive tasks, once they are mastered. Skills for performing repetitive tasks are repressed in subconscious memory, permitting individuals to pay attention to things other than performance of repetitive tasks (Johnson 1983). Ironically as a result, what most individuals

think about the most is what they will do, but what they do the most is what they think about the least.

In complex decision situations, individuals create stereotypes as a defense mechanism to deal with complexity. For the average person, stereotyping is likely to begin when seven (plus or minus two) objects or digits are involved in a decision—this number being the information processing capacity of the average individual (Miller 1956). As decision complexity increases beyond this point, people become more conservative and apply more subjective criteria which are further and further removed from reality (Filley, House, and Kerr 1976). Furthermore, since the correctness of outcomes from innovative ideas can rarely be judged, the perceived legitimacy of the decision *process* becomes the dominant evaluation criterion. Thus, as March (1981) and Janis (1982) point out, as decision complexity increases, solutions become increasingly error prone, means become more important than ends, and rationalization replaces rationality.

It is generally believed that crises, dissatisfaction, tension, or significant external stress are the major preconditions for stimulating people to act. March and Simon (1958) set forth the most widely accepted model by arguing that dissatisfaction with existing conditions stimulates people to search for improved conditions, and they will cease searching when a satisfactory result is found. A satisfactory result is a function of a person's aspiration level, which Lewin et. al. (1944) indicated is a product of all past successes and failures that people have experienced. If this model is correct (and most believe it is), then scholars and practitioners must wrestle with another basic problem.

This model assumes that when people reach a threshold of dissatisfaction with existing conditions, they will initiate action to resolve their dissatisfaction. However, because individuals unconsciously adapt to slowly changing environments, their thresholds for action are often not triggered while they adapt over time. In this sense, individuals are much like frogs. Although we know of no empirical support for the frog story developed by Gregory Bateson, it goes as follows.

> When frogs are placed into a boiling pail of water, they jump out—they don't want to boil to death.
>
> However, when frogs are placed into a cold pail of water, and the pail is placed on a stove with the heat turned very low, over time the frogs will boil to death.

Cognitive psychologists have found that individuals have widely varying and manipulable adaptation levels (Helson 1948, 1964). When exposed over time to a set of stimuli that deteriorate very gradually, people do not percieve the gradual changes—they unconsciously adapt to the worsening conditions. Their threshold to tolerate pain, discomfort, or dissatisfaction is not reached. As a consequence, they do not move into action to correct their situation, which over time may become deplorable. Opportunities for innovative ideas are not recognized, problems swell into metaproblems, and at the extreme, catastrophes are sometimes necessary to reach the action threshold (Van de Ven 1980b).

These worsening conditions are sometimes monitored by various corporate planning and management information units and distributed to personnel in quantitative MIS reports of financial and performance trends. However, these impersonal statistical reports only increase the numbness of organizational participants and raise the false expectation that if someone is measuring the trends then someone must be doing something about them.

When situations have deteriorated to the point of actually triggering peoples' action thresholds, innovative ideas turn out to be crisis management ideas. As Janis (1982) describes, such decision processes are dominated by defense mechanisms of isolation,

projection, stereotyping, displacement, and retrospective rationalizations to avoid negative evaluations. As a result, the solutions that emerge from such "innovative" ideas are likely to be "mistakes."

*Group and Organizational Limitations*

At the group and organizational levels, the problems of inertia, conformity, and incompatible preferences are added to the above physiological limitations of human beings in managing attention. As Janis (1982) has clearly shown, groups place strong conformity pressures on members, who collectively conform to one another without them knowing it. Indeed, the classic study by Pelz and Andrews (1966) found that a heterogeneous group of interdisciplinary scientists when working together daily became homogeneous in perspective and approach to problems in as little as three years. Groups minimize internal conflict and focus on issues that maximize consensus. "Group Think" is not only partly a product of these internal conformity pressures, but also of external conflict—"out-group" conflict stimulates "in-group" cohesion (Coser 1959). Consequently, it is exceedingly difficult for groups to entertain threatening information, which is inherent in most innovative ideas.

Organizational structures and systems serve to sort attention. They focus efforts in prescribed areas and blind people to other issues by influencing perceptions, values, and beliefs. Many organizational systems consist of programs, which create slack through efficient repetitive use of procedures believed to lead to success (Cyert and March 1963). But as Starbuck (1983) argues, the programs do not necessarily address causal factors. Instead, the programs tend to be more like superstitious learning, recreating actions which may have little to do with previous success and nothing to do with future success. As a result, the older, larger, and more successful organizations become, the more likely they are to have a large repertoire of structures and systems which discourage innovation while encouraging tinkering. For example, strategic planning *systems* often drive out strategic thinking as participants "go through the numbers" of completing yearly planning forms and review cycles.

The implication is that without the intervention of leadership (discussed below), structures and systems focus the attention of organizational members to routine, not innovative activities. For all the rational virtues that structures and systems provide to maintain existing organizational practices, these "action generators" make organizational participants inattentive to shifts in organizational environments and the need for innovation (Starbuck 1983). It is surprising that we know so little about the management of attention. However, several useful prescriptions have been made.

*Ways to Manage Attention*

At a recent conference on strategic decision making (Pennings 1985), Paul Lawrence reported that in his consulting practice he usually focuses on what management is *not* paying attention to. Similarly based on his observations in consulting with large organizations, Richard Normann observed that well-managed companies are not only close to their customers, they search out and focus on their *most demanding customers*. Empirically, von Hippel (1977) has shown that ideas for most new product innovations come from customers. Being exposed face-to-face with demanding customers or consultants increases the likelihood that the action threshold of organizational participants will be triggered and will stimulate them to pay attention to changing environmental conditions or customer needs. In general, we would expect that *direct personal confrontations with problem sources* are needed to reach the threshold of concern and appreciation required to motivate people to act (Van de Ven 1980b).

However, while face-to-face confrontations with problems may trigger action thresholds, they also create stress. One must therefore examine the effects of stress on the

innovative process. Janis (1985) outlines five basic patterns of coping with stress, and states that only the vigilance pattern generally leads to decisions that meet the main criteria for sound decision making. Vigilance involves an extended search and assimilation of information, and a careful appraisal of alternatives before a choice is made. Janis proposes that vigilance tends to occur under conditions of moderate stress, and when there may be sufficient time and slack resources to make decisions. Under conditions of no slack capacity or short-time horizons (which produce stress) the decision process will resemble crisis decision-making—resulting in significant implementation errors (Hrebiniak and Joyce 1984).

Argyris and Schon (1982) focus on single loop and double loop learning models for managing attention that may improve the innovation process. In single loop learning, no change in criteria of effective performance takes place. Single loop learning represents conventional monitoring activity, with actions taken based on the findings of the monitoring system. Because it does not question the criteria of evaluation, single loop learning leads to the organizational inertia which Starbuck (1983) indicates must be unlearned before change can occur. Double loop learning involves a change in the criteria of evaluation. Past practices are called into question, new assuptions about the organization are raised, and significant changes in strategy are believed to be possible.

While double loop learning can lead to change, it can also lead to low trust, defensive behavior, undiscussibles, and to bypass tactics. Thus, the management of attention must be concerned not only with triggering the action thresholds of organizational participants, but also of channeling that action toward constructive ends. Constructive attention management is a function of how two other central problems are addressed: part-whole relations and institutional leadership—which we will now discuss.

## The Management of Part-Whole Relationships

*Proliferation of ideas, people, and transactions over time is a pervasive but little understood characterstic of the innovation process, and with it come complexity and interdependence—and the basic structural problem of managing part-whole relations.*

The proliferation of ideas is frequently observed in a single individual who works to develop an innovation from concept to reality. Over time the individual develops a mosaic of perspectives, revisions, extensions, and applications of the initial innovative idea—and they accumulate into a complex set of interdependent options. However, as the discussion of managing ideas into good currency implies, innovation is not an individual activity—it is a collective achievement. Therefore, over time there is also a proliferation of people (with diverse skills, resources, and interests) who become involved in the innovation process. When a single innovative idea is expressed to others, it proliferates into multiple ideas because people have diverse frames of reference, or interpretive schemas, that filter their perceptions. These differing perceptions and frames of reference are amplified by the proliferation of transactions or relationships among people and organizational units that occur as the innovation unfolds. Indeed, management of the innovation process can be viewed as managing increasing bundles of transactions over time.

Transactions are "deals" or exchanges which tie people together within an institutional framework (which is context). John R. Commons (1951), the originator of the concept, argued that transactions are dynamic and go through three temporal stages: negotiations, agreements, and administration. Most transactions do not follow a simple linear progression through these stages. The more novel and complex the innovative idea, the more often trial-and-error cycles of renegotiation, recommitment, and re-administration of transactions will occur. Moreover, the selection of certain kinds of transactions is always conditioned by the range of past experiences and current

situations to which individuals have been exposed. Therefore, people have a conservative bias to enter into transactions with parties they know, trust, and with whom they have had successful experiences. As a consequence, what may start as an interim solution to an immediate problem often proliferates over time into a web of complex and interdependent transactions among the parties involved.

There is an important connection between transactions and organizations. Transactions are the micro elements of macro organizational arrangements. Just as the development of an innovation might be viewed as a bundle of proliferating transactions over time, so also, is there proliferation of functions and roles to manage this complex and interdependent bundle of transactions in the institution that houses the innovation.

The prevailing approach for handling this complexity and interdependence is to divide the labor among specialists who are best qualified to perform unique tasks and then to integrate the specialized parts to recreate the whole. The objective, of course, is to develop synergy in managing complexity and interdependence with an organizational design where the whole is greater than the sum of its parts. However, the whole often turns out to be less than or a meaningless sum of the parts because the parts do not add to, but subtract from one another (Hackman 1984). This result has been obtained not only when summing the products of differentiated units within organizations, but also the benefits member firms derive from associating with special interest groups (Maitland 1983, 1985). Kanter (1983), Tushman and Romanelli (1983), and Peters and Waterman (1982) have shown that this "segmentalist" design logic is severely flawed for managing highly complex and interdependent activities. *Perhaps the most significant structural problem in managing complex organizations today, and innovation in particular, is the management of part-whole relations.*

For example, the comptroller's office detects an irregularity of spending by a subunit and thereby eliminates an innovative "skunkworks" group; a new product may have been designed and tested, but runs into problems when placed into production because R & D and engineering overlooked a design flaw; the development of a major system may be ready for production, but subcontractors of components may not be able to deliver on schedule or there may be material defects in vendors' parts. Typical attributions for these problems include: lack of communication or misunderstandings between scientific, engineering, manufacturing, marketing, vendors and customers on the nature or status of the innovation; unexpected delays and errors in certain developmental stages that complicate further errors and rework in subsequent stages; incompatible organizational funding, control, and reward policies; and ultimately significant cost over-runs and delayed introductions into the market.

Peters and Waterman (1982) dramatized this problem of part-whole relationships with an example of a product innovation which required 223 reviews and approvals among 17 standing committees in order to develop it from concept to market reality. Moreover, they state that

> The irony, and the tragedy, is that each of the 223 linkages taken by itself makes perfectly good sense. Well-meaning, rational people designed each link for a reason that made sense at the time . . . . The trouble is that the total picture as it inexorably emerged . . . captures action like a fly in a spider's web and drains the life out of it. (Peters and Waterman 1982 pp. 18–19).

This example clearly illustrates a basic principle of contradictory part-whole relationships—*impeccable micro-logic often creates macro nonsense*, and vice versa.

*Is there a way to avoid having the whole be less than or a meaningless sum of its parts*? Perhaps a way is needed to design the whole into the parts, as Gareth Morgan (1983a, b, 1984) has been pursuing with the concept of a *hologram*. He concluded that the

brain, with its incredible complexity, manages that complexity by placing the essential elements of the whole into each of its parts—it is a hologram.

Most organizations, however, are not designed with this logic, but if possible ought to be. The hologram metaphor emphasizes that organization design for innovation is not a discrete event but a process for integrating all the essential functions, organizational units, and resources needed to manage an innovation from beginning to end. It requires a significant departure from traditional approaches to organizing innovation.

Traditionally the innovation process has been viewed as a sequence of separable stages (e.g., design, production, and marketing) linked by relatively minor transitions to make adjustments between stages. There are two basic variations of this design for product innovation. First, there is the technology-driven model where new ideas are developed in the R&D department, sent to engineering and manufacturing to produce the innovation, and then on to marketing for sales and distribution to customers. The second, and currently more popular, design is the customer or need-driven model, where marketing comes up with new ideas as a result of close interactions with customers, which in turn are sent to R&D for prototype development and then to engineering and manufacturing for production. Galbraith (1982) points out that the question of whether innovations are stimulated by technology or customer need is debatable.

> "But this argument misses the point." As reproduced in Figure 2, "the debate is over whether [technology] or [need] drives the downstream efforts. This thinking is linear and sequential. Instead, the model suggested here is shown in Figure [2b]. That is, for innovation to occur, knowledge of all key components is simultaneously coupled. And the best way to maximize communication among the components is to have the communication occur intrapersonally—that is, within one person's mind. If this is impossible, then as few people as possible should have to communicate or interact. (Galbraith 1982, pp. 16–17).

As Galbraith implies, with the hologram metaphor the innovation process is viewed as consisting of iterations of inseparable and simultaneously-coupled stages (or functions) linked by a major ongoing transition process. Whereas the mechanical metaphor of an assembly line of stages characterizes most current views of the innovation process, the biological metaphor of a hologram challenges scholars and practitioners to find ways to place essential characteristics of the whole into each of the parts.

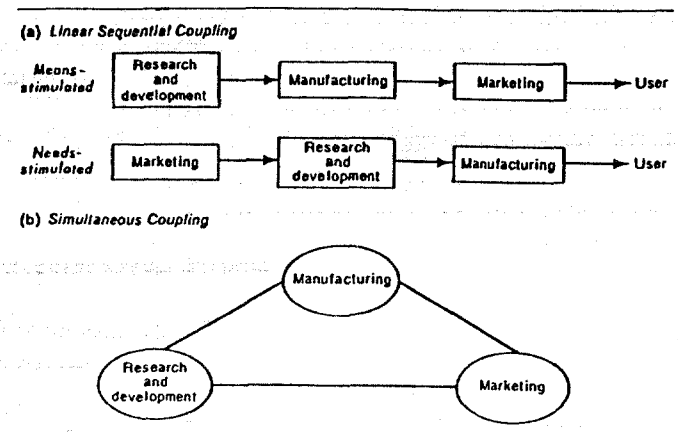


FIGURE 2. Linear Sequential Coupling Compared with Simultaneous Coupling of Knowledge. Source: Jay R. Galbraith (1982).

Although very little is known about how to design holographic organizations, four inter-related design principles have been suggested by Morgan (1985) and others: self-organizing units, redundant functions, requisite variety, and temporal linkage.

First, the hologram metaphor directs attention to identifying and grouping together all the key resources and interdependent functions needed to develop an innovation into one organizational unit, so that it can operate as if it were an *autonomous unit*. (Of course, no organizational unit is ever completely autonomous.) The principle of autonomous work groups has been developed largely by Trist (1981), and is consistent with Thompson's (1967) logical design principle of placing reciprocally-interdependent activities closely together into a common unit in order to minimize coordination costs. By definition, autonomous groups are self-organizing, which implies that management follows the "principle of minimum intervention" (Hrebiniak and Joyce 1984, p. 8). This allows the group to self-organize and choose courses of action to solve its problems within an overall mission and set of constraints prescribed for the unit by the larger organization.

Second, flexibility and a capacity for self-organizing is needed by creating *redundant functions*, which means that people develop an understanding of the essential considerations and constraints of all aspects of the innovation in addition to those immediately needed to perform their individual assignments. Redundant functions does not mean duplication or spare parts as may be implied by the mechanistic metaphor, nor does it eliminate the need for people to have uniquely-specialized technical competencies. It means that all members of an innovation unit develop the capacity to "think globally while acting locally." The principle of redundant functions is achieved through training, socialization, and inclusion into the innovation unit so that each member not only comes to know how his or her function relates to each other functional specialty, but also understands the essential master blueprint of the overall innovation. The former is needed for interdependent action; the latter is essential for survival and reproduction of the innovative effort.

Third, following Ashby's (1956) principle of *requisite variety*, learning is enhanced when a similar degree of complexity in the environment is built into the organizational unit. This principle is a reflection of the fact that any autonomous organizational unit at one level is a dependent part of a larger social system at a more macro level of analysis. Requisite variety means placing critical dimensions of the whole environment into the unit, which permits the unit to develop and store rich patterns of information and uncertainty that are needed in order to detect and correct errors existing in the environment. The principle of requisite variety is not achieved by assigning the task of environmental scanning to one or a few boundary spanners, for that makes the unit dependent upon the "enactments" (Weick 1979) of only one or a few individuals whose frames of reference invariably filter only selective aspects of the environment. Requisite variety is more nearly achieved by making environmental scanning a responsibility of all unit members, and by recruiting personnel within the innovation unit who understand and have access to each of the key environmental stakeholder groups or issues that affect the innovation's development.

Whereas the principles of redundant functions and requisite variety create the slack needed to integrate members of the unit and between the unit and its environment (respectively), the principle of *temporal linkage* integrates parts of time (past, present, and future events) into an overall chronology of the innovation process. While innovations are typically viewed as making additions to existing arrangements, Albert (1984c) proposes another arithmetic for linking the past, present and future. Given a world of scarcity, Albert (1984a, b) notes that the implementation of innovations often results in eliminations, replacements, or transformations of existing arrangements. As a consequence, the management of innovation must also be the management of termina-

tion, and of transitioning people, programs, and investments from commitments in the past toward the future. In common social life, funerals and wakes are used to commemorate and bereave the passing of loved ones and to make graceful transitions into the future. As Albert suggests, there is a need to create funerals, celebrations, and transitional rituals that commemorate the ideas, programs, and commitments falling out of currency in order to create opportunities for ushering in those that must gain good currency for an innovation to succeed.

### Institutional Leadership and Innovation Context

Innovation is not the enterprise of a single entrepreneur. Instead, it is a network-building effort that centers on the creation, adoption, and sustained implementation of a set of ideas among people who, through transactions, become sufficiently committed to these ideas to transform them into "good currency." Following holographic principles, this network-building activity must occur both within the organization and in the larger community of which it is a part. *Creating these intra- and extra-organizational infrastructures in which innovation can flourish takes us directly to the strategic problem of innovation, which is institutional leadership.*

The extra-organizational context includes the broad cultural and resource endowments that society provides, including laws, government regulations, distributions of knowledge and resources, and the structure of the industry in which the innovation is located. Research by Ruttan and Hayami (1983) and Trist (1981) suggests that innovation does not exist in a vacuum and that institutional innovation is in great measure a reflection of the amount of support an organization can draw from its larger community. Collective action among institutional leaders within a community becomes critical in the long run to create the social, economic, and political infrastructure a community needs in order to sustain its members (Astley and Van de Ven 1983). In addition, as Aldrich (1979) and Erickson and Maitland (1982) indicate, a broad population or industry purview is needed to understand the societal demographic characteristics that facilitate and inhibit innovation.

Within the organization, institutional leadership is critical in creating a cultural context that fosters innovation, and in establishing organizational strategy, structure, and systems that facilitate innovation. As Hackman (1984, p. 40) points out, "an unsupportive organizational context can easily undermine the positive features of even a well-designed team." There is a growing recognition that innovation requires a special kind of supportive leadership.

> This type of leadership offers a vision of what could be and gives a sense of purpose and meaning to those who would share that vision. It builds commitment, enthusiasm, and excitment. It creates a hope in the future and a belief that the world is knowable, understandable, and manageable. The collective energy that transforming leadership generates, empowers those who participate in the process. There is hope, there is optimism, there is energy (Roberts 1984, p. 3).

Institutional leadership goes to the essence of the process of institutionalization. It is often thought that an organization loses something (becomes rigid, inflexible, and loses it ability to be innovative) when institutionalization sets in. This may be true if an organization is viewed as a mechanistic, efficiency-driven tool. But, as Selznick (1957) argued, an organization does not become an "institution" until it becomes infused with value; i.e., prized not as a tool alone, but as a source of direct personal gratification, and as a vehicle for group integrity. By plan or default, this infusion of norms and values into an organization takes place over time, and produces a distinct identity, outlook, habits, and commitments for its participants—coloring as it does all aspects of organizational life, and giving it a social integration that goes far beyond the formal command structure and instrumental functions of the organization.

Institutional leadership is particularly needed for organizational innovation, which represents key periods of development and transition when the organization is open to or forced to consider alternative ways of doing things. During these periods, Selznick emphasized that the central and distinctive responsibility of institutional leadership is the creation of the organization's character or culture. This responsibility is carried out through four key functions: defining the institution's mission, embodying purpose into the organization's structure and systems, defending the institution's integrity, and ordering internal conflict. Selznick (1957, p. 62) reports that when institutional leaders default in performing these functions, the organization may drift. "A set of beliefs, values and guiding principles may emerge in the organization that are counterproductive to the organization's mission or distinctive competence. As institutionalization progresses the enterprise takes on a special character, and this means that it becomes peculiarly competent (or incompetent) to do a particular kind of work" (Selznick 1957, p. 139). Organization drift is accompanied by loss of the institution's integrity, opportunism, and ultimately, loss of distinctive competence.

Lodahl and Mitchell (1980, pp. 203–204) insightfully apply Selznick's perspective by distinguishing how institutional and technical processes come into play to transform innovative ideas into a set of guiding ideals—see Figure 3. First there are the founding ideals for an innovation or an enterprise, followed by the recruitment and socialization of members to serve those ideas. Leadership and formalization guide and stabilize the enterprise.

When viewed as a set of technical or instrumental tasks, the process is operationalized into setting clear goals or ends to be achieved; establishing impersonal and universal criteria for recruitment, developing clear rules and procedures for learning and socialization; analytical problem solving and decision making; and routinizing activities in order to reduce uncertainty. Institutional processes are very different from this well-known technical approach.

As Figure 3 illustrates, institutional processes focus on the creation of an ideology to support the founding ideals; the use of personal networks and value-based criteria for

| INSTITUTIONAL PROCESSES | IDEA | TECHNICAL PROCESSES |
|---|---|---|
| CREATION, ELABORATION OF IDEOLOGY | FOUNDING IDEALS | STATEMENT OF ORGANIZATIONAL GOALS |
| USE OF PERSONAL NETWORKS; SELECTION BASED ON VALUES AND IDEALS | RECRUITMENT | BROAD SEARCH: USE OF UNIVERSALISTIC CRITERIA |
| FACE-TO-FACE CONTACT WITH FOUNDERS: SHARING RITUALS, SYMBOLS | SOCIALIZATION | RULES AND PROCEDURES LEARNED THROUGH COLLEAGUES |
| CHARISMATIC, MYTHIC IMAGES (TRANSFORMING) | LEADERSHIP | PROBLEM SOLVING AND CONSENSUS MAKING (TRANSACTIONAL) |
| IDEALS PARAMOUNT: STRUCTURE TENTATIVE | FORMALIZATION | EARLY ROUTINIZATION; UNCERTAINTY REDUCTION |

FIGURE 3. Institutional and Technical Processes. Source: T. Lodahl and S. Mitchell (1980).

recruitment; socialization and learning by sharing rituals and symbols; charismatic leadership; and the infusion of values as paramount to structure and formalize activities.

Lodahl and Mitchell (1980, p. 204) point out that an innovation is an institutional success to the degree that it exhibits authenticity, functionality, and flexibility over time. Authenticity requires that the innovation embodies the organization's ideas; functionality requires that the innovation work; and flexibility requires that the innovation can incorporate the inputs and suggestions of its members. If these tests are met, organizational members will make a commitment to the innovation. In contrast, if institutional skills are not used while technical skills are in operation, the innovation may be an organizational success but an institutional failure. In that case, there will be evidence of drift and disillusionment. Such a result will be characterized by individual self-interest, differentiation, and technical efficiency.

These distinctions between institutional and technical processes have three significant implications for addressing the problems of managing attention, ideas, and part-whole relations discussed in previous sections. These implications draw upon cybernetic principles and the hologram metaphor, as Morgan (1983b, 1984) proposes.

First, organizational members can develop a capacity to control and regulate their own behavior through a process of *negative feedback*, which means that goals are achieved by avoiding not achieving the goal. In other words, deviations in one direction initiate action in the opposite direction at every step in performing an activity so that in the end no error remains. In order for learning through negative feedback to occur, an organization must have values and standards which define the critical limits within which attention to innovative ideas is to focus. Whereas technical processes focus attention on clear-cut goals and targets to be achieved, institutional processes define the constraints to avoid in terms of values and limits. Institutional leadership thus involves a choice of limits (issues to avoid) rather than a choice of ends. As Burgelman (1984, p. 1349) points out, "top management's critical contribution consists in strategic recognition rather than planning." As a result, a space of possible actions is defined which leaves room for innovative ideas to develop and to be tested against these constraints.

Second, whereas single loop learning involves an ability to detect and correct deviations from a set of values and norms, double loop learning occurs when the organization also learns how to detect and correct errors in the operating norms themselves. This permits an institution to adjust and change the ideas considered legitimate or to have good currency.

From an institutional view legitimate error stems from the uncertainty inherent in the nature of a situation. The major problem in dealing with uncertainty is maintaining a balance on organizational diversity and order over time (Burgelman 1984). Diversity results primarily from autonomous initiatives of technical units. Order results from imposing standards and a concept of strategy on the organization. Managing this diversity requires framing ideas and problems so that they can be approached through experimentation and selection. The process of double-loop learning is facilitated by probing into various dimensions of a situation, and of promoting constructive conflict and debate between advocates of competing perspectives. Competing action strategies lead to reconsideration of the organization's mission, and perhaps a reformulation of that mission.

Finally, although technical processes of formalization press to reduce uncertainty, institutional processes attempt to preserve it. Just as necessity is the mother of invention, preserving the same degrees of uncertainty, diversity, or turbulence within an organization that is present in the environment are major sources of creativity and long-run viability for an organization. Embracing uncertainty is achieved by maintain-

ing balance among innovative subunits, each designed according to the holographic principles of autonomous groups, requisite variety, and redundant functions discussed above. Application of these principles results in mirroring the turbulence present in the whole environment into the decision processes and other activities of each of the organization's parts. As a consequence, innovation is enhanced because organizational units are presented with the whole "law of the situation."

## Concluding Discussion

Innovation has been defined as the development and implementation of new ideas by people who over time engage in transactions with others within an institutional context. This definition is particularly relevant to the general manager for it applies to a wide variety of technical, product, process, and administrative kinds of innovations that typically engage the general manager. From a managerial viewpoint, to understand the process of innovation is to be able to answer three questions: How do innovations develop over time? What kinds of problems will most likely be encountered as the innovation process unfolds? What responses are appropriate for managing these problems? Partial answers to these questions can be obtained by undertaking longitudinal research which systematically examines the innovation process, problems, and outcomes over time. Undertaking this research requires a conceptual framework to guide the investigation. The main purpose of this paper has been to develop such a framework by suggesting what key concepts, problems, and managerial responses should be the guiding focus to conduct longitudinal research on the management of innovation.

As our definition of innovation suggests, four basic concepts are central to studying the innovational process over time: ideas, people, transactions, and context. Associated with these four concepts are four central problems in the management of innovation: developing ideas into good currency, managing attention, part-whole relationships, and institutional leadership. Although these concepts and problems have diverse origins in the literature, previously they have not been combined into an interdependent set of critical concepts and problems for studying innovation management.

An invention or creative idea does not become an innovation until it is implemented or institutionalized. Indeed by most standards, the success of an innovation is largely defined in terms of the degree to which it gains good currency, i.e., becomes an implemented reality and is incorporated into the taken-for-granted assumptions and thought structure of organizational practice. Thus, a key measure of innovation success or outcome is the currency of the idea, and a basic research question is how and why do some new ideas gain good currency while the majority do not? Based on work by Schon (1971), Quinn (1980), and others, we think the answer requires longitudinal study of the social and political processes by which people become invested in or attached to new ideas and push them into good currency.

But what leads people to pay attention to new ideas? This is the second major problem to be addressed in a research program on innovation. We argued that an understanding of this issue should begin with an appreciation of the physiological limitations of human beings to pay attention to nonroutine issues, and their corresponding inertial forces in organizational life. The more specialized, insulated, and stable an individual's job, the less likely the individual will recognize a need for change or pay attention to innovative ideas. It was proposed that people will pay attention to new ideas the more they experience personal confrontations with sources of problems, opportunities, and threats which trigger peoples' action thresholds to pay attention and recognize the need for innovation.

Once people begin to pay attention to new ideas and become involved in a social-political process with others to push their ideas into good currency, a third

problem of part-whole relationships emerges. A common characteristic in the development of innovations is that multiple functions, resources, and disciplines are necessary to transform innovative ideas into reality—so much so that individuals involved in specific transactions or parts of the innovation lose sight of the whole innovative effort. If left to themselves, they will design impeccable micro-structures for the innovation process that often result in macro nonsense. The hologram metaphor was proposed for designing the innovation process in such a way that more of the whole is structured into each of the proliferating parts. In particular, application of four holographic principles was proposed for managing part-whole relationships: self-organizing groups, redundant functions, requisite variety, and temporal linkage.

However, these holographic principles for designing innovation units simultaneously require the creation of an institutional context that fosters innovation and that links these self-organizing innovative units into a larger and more encompassing organizational mission and strategy. The creation of this macro context for innovation points to the need to understand and study a fourth central problem, which is institutional leadership. Innovations must not only adapt to existing organizational and industrial arrangements, but they also transform the structure and practices of these environments. The strategic problem for institutional leaders is one of creating an infrastructure that is conducive to innovation and organizational learning.

Three cybernetic principles were proposed to develop this infrastructure. First, the principle of negative feedback suggests that a clear set of values and standards are needed which define the critical limits within which organizational innovations and operations are to be maintained. Second, an experimentation-and-selection approach is needed so that the organization develops a capacity for double-loop learning, i.e., learning how to detect and correct errors in the guiding standards themselves. Third, innovation requires preserving (not reducing) the uncertainty and diversity in the environment within the organization because necessity is the mother of invention. Embracing uncertainty can be achieved at the macro level through the principles of requisite variety and redundancy of functions.

It should be recognized that this has been a speculative essay on key problems in the management of innovation. Little empirical evidence is presently available to substantiate these problems, their implications, and proposed solutions. However, the essay has been productive in suggesting a core set of concepts, problems, and propositions to study the process of innovation over time, which is presently being undertaken by a large group of investigators at the University of Minnesota. A description of the operational framework being used in this longitudinal research is available (Van de Ven and Associates 1984). As this research progresses we hope to provide systematic evidence to improve our understanding of the central problems in the management of innovation discussed here.[1]

[1] The author wishes to gratefully recognize the stimulation of ideas for this paper from faculty and student colleagues involved in the Minnesota Innovation Research Program. Helpful comments on earlier drafts of this paper were provided by George Huber, William Joyce, Arie Lewin, Kenneth Mackenzie, and Donald Schon. This research program is supported in part by a major grant from the Organizational Effectiveness Research Programs, Office of Naval Research (Code 4420E), under Contract No. N00014-84-K-0016. Additional research support is being provided by 3M, Honeywell, Control Data, Dayton-Hudson, First Bank Systems, Cenex, Dyco Petroleum, and ADC Corporations.

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## Armand HATCHUEL

Armand Hatchuel is Full Professor and co-head of the chair of Design theory and methods for innovation at Mines ParisTech-PSL Research University. The chair is mainly sponsored by industrial partners. Beyond decision and optimization theory, he has developed with Benoit Weil, a new design theory (called C-K theory) that models creative reasoning and the generative logic of new objects. C-K theory is discussed in Engineering, cognitive psychology, management and philosophical journals. Applications of C-K theory are now widely documented. Armand Hatchuel has also developed a new epistemological perspective on collective action and he appears as one of the organizational thinkers whose work is described in the Palgrave Handbook of organizational thinking (2017). He has published extensively and is member of journal and scientific boards. He co-founded the SIG Design theory workshop which has become a major annual meeting in the field. They had a strong impact on how creative design is organized in worldwide companies He received several awards. He is fellow of the national academy of technologies of France and fellow of the Design Society. He has recently co-authored:" *Strategic Management of innovation and design*", (2013) at Cambridge University Press and "*Design theory*" at Springer (2017). He has been honoured as knight of the legion of honor by the French government.

**Title of the Presentation:**

Design theory and the art tradition

**Synopsis:**

This tutorial highlights key points of the history and forms of what has been called industrial design or "design" in some national cultures. Actually, this movement combine artistic and engineering tradition in different ways. Based on recently literature, the course presents the contribution of design theory to explain the cognitive and theoretical understanding of these design forms and their impacts on society.

**Main References/ Further readings:**

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# Deconstructing meaning: Industrial design as Adornment and Wit

Armand Hatchuel

# Deconstructing meaning: industrial design as Adornment and wit.

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Inventor*, n. A person who makes*
*an ingenious arrangement*
*of wheels, levers and springs*
*and believes it civilization.*

Ambrose Bierce. The Devil's Dictionary.

**Abstract**

In this paper we present new theoretical perspectives about industrial design. First, we establish that antinomies about function, form and meaning cannot offer a theory of industrial design. Then we bear on advances in Design theory in the literature of engineering design to find out *universal features of design* which are common to industrial design, Architecture and Engineering. Taking into account social and cognitive contexts, we identify the dilemma that is specific of industrial design. This dilemma can be solved in two ways that we define as "adornement" and "wit" which differ by how *the identity of objects* is maintained or challenged by design. Each way corresponds to different types of *rhetoric* -classic and conceptist- that we identify. The combination of adornment and wit explains the generative power of industrial design and its paradoxical situation: *neither Art, neither engineering*. Moreover, the academic identity of industrial design research can be clarified within the traditions of Design theory, anthropology and rhetoric.

## Introduction: the academic trouble with industrial design

In 1993, Paris hosted a great exhibition [1] about industrial Design[2]. In the preface of the book of the exhibition, the anthropologist Marc Augé reacted to Jocelyn de Noblet's[3] definition of industrial design: " *Industrial Design is how a large variety of people label objects that from their points of view produce meaning*"[4]. The anthropologist asked: "*what is that meaning that is claimed to be produced by Industrial design*?" Similar questions are repeatedly acknowledged by any handbook or anthology of industrial design. History does, of course, cast some light on the emergence of industrial design (Forty 1988, Margolin 2009), but it does nothing to make it less complex. It is interesting to trace the traditions and the

[1] "Design, le miroir du Siècle", our translation: "Industrial Design, a mirror of the century"
[2] In French, the word "design" means "industrial design". When Design is used in expressions like "architectural design", engineering design "organizational design, the word "conception" is a better translation.
[3] The editor of the catalogue of the exhibition
[4] Our translation.

many break-off points in the history of industrial design (Forty 1988), but this simply points to the unexpected alchemy that forged this tradition. It leaves research with the task of finding the *identity of the whole*.

In this paper, we present new theoretical perspectives about industrial design. Our focus is to discuss the nature of what is traditionally called "industrial design" or simply "design"[5] since the beginning of the 20th century. This tradition is clearly distinct from Engineering design or Architecture: it is not taught in the same schools and corresponds to completely different social roles than the two last ones. However, to highlight the specificities of industrial design, we will reject the classic antinomies that oppose form, function and meaning. We will introduce a theoretical view of design that is independent of what is designed. Still, it will help us to contrast industrial design from other types of design.

Is there really a need for an academic definition as the lack of one has not stopped industrial design from developing professionally? The answer is positive if we consider that this gap has curbed true academic recognition of industrial design as full discipline and area of research. Moreover, the growing development of doctoral education visibilized the theoretical problems of industrial design, but it has done less to foster their solution and, in Margolin's terms, to avoid research "*remaining equally cacophonous and without a set of shared problematic*s" (Margolin 2010).

For sure, classic definitions of Design are too broad and not specific enough to support sustained and focused academic work. Margolin (margolin 2010) mentioned two definitions which reflect shared views about design and yet lack academic analytical power if one seeks to define industrial design. The first one is Richard Buchanan's: "*Design is a human power of conceiving, planning and making products that serve human beings in the accomplishement of their individual and collective purpose*". The second definition also quoted by Margolin (Margolin 2010) is Bruce Archer's one who states that "*Design is the combined embodiment of configuration, composition, structure, purpose, value and meaning in man-made things and systems*". Buchanan's and Archer's definitions follow two different approaches that deserve to be discussed:

- The first definition remains too broad and misses the specificity of Design. This may explain why Richard Buchanan (quoted by Margolin 2010) stands that "*Design does not have a subject matter in the traditional sense of other disciplines and fields of learning*". Such proposition puts design under dark academic fate, but it is highly questionable. During the 20th century disciplines like Decision Theory, Cognition Science or the psychology of creativity, which share common features with design, have all been able to build a subject matter in the "traditional sense".

- Archer's definition links the identity of design to a *specific list of themes, issues and production variables*. This approach is similar to Vitruvius's archetypal definition of Architecture (Vitruvius 2001)[6]. Yet, such approach does not help to distinguish industrial

[5] In this paper, we will use the term industrial design to describe this tradition. The word "design", when used alone designates the general category that we find in expressions like architectural design, engineering design, organizational design, concept design and so on.

[6] In the time of Vitruvius (1st century ce.) Architecture included machine design, time measurement, war defences, water engineering and so on… Vitruvius claimed that architecture was different from the crafts that it mobilized. Above all, he stated that the mission of the architect was to that guide and renew the art of building by having in mind specific philosophical categories (the famous six functions or themes of architecture, most of them coming from Greek thinkers)

design from other Design professions, like architects and engineers, who share such list of themes or goals.

What we attempt in our research is to elaborate a definition of industrial design that addresses universal issues and yet explains its differences with other traditions of Design. In the literature and in practice, this definition is usually built upon classical antinomies between form, function and meaning. They have built the discourse about industrial design but lack solid academic ground..

## • A critical review of function, form and meaning

a) The most popular antinomy that was used to define industrial design is the opposition between *form* and *function*. Form freed from function was the supposed realm of industrial design. But this idea was soon rejected by the modernist motto – *"form follows function"* – uttered by the architect Louis Sullivan. Beyond the controversy, it should be acknowledged that from *a theoretical* point of view neither function, nor form, have a clear status. The notion of function played an important role in classic engineering design (Hatchuel et al. 2012) but and it was also used to organize work division between engineers and industrial designers, on the grounds that 'functions' relate to objects' utilitarian aspects and technical necessities, as opposed to aesthetic or other sensible aspects which are not considered 'functional'. This classic view has been reassessed by authors insisting more on semiotic and semantic aspects of industrial design (Krippendorff 1989). Indeed, such opposition has its roots in the romantic revolution that followed the British industrial revolution; the latter criticized manufactured products with "a poor design" and praised *splendour* against *utility* (Ruskin 2007). In later periods, utility was also named *function*; and splendour, *esthetics*. However, it can be argued that objects have *aesthetic functions* whenever there are aesthetic intentions (or perceptions) in their design. Any aesthetic value *must* be converted into technical or functional needs. Take a colour, carefully selected to express particular emotions: work has to be done on issues such as its stability, unwanted reflections that reduce its impact or the type of surface that enhances its value. To put it briefly, beauty can be useful (for instance when it provokes care and respect from users) and utility (like power and speed) can be beautiful (as claimed by the futurist manifesto in 1909). 'Function' is the name that we give to any *value* that is used to design, judge or experience an object [7]. However, the language of value cannot fully account for *the identity of objects* (Le Masson, Hatchuel and Weil 2010): we can recognize "chairs", "houses", "pens" even if the values they incorporate or signal are radically changed. We will come back later to this important notion.

b) Krippendorf (Krippendorf 1989) introduced the distinction between *Form and Meaning* and argued tha "*Form, not function, is related to meaning*". This view frees industrial

[7] Despite this, can the expression "form follows function" sometimes be considered meaningful? The answer is negative once again, because even if we retain the traditional meaning of 'function', the expression is only valid in very special circumstances. It is really astonishing that it still has such resonance, despite the fact that it is clearly contradicted all the time. All engineers know that there is not necessarily a link between the functional analysis of a system and the physical or geometrical shape it takes. The same function can be catered for using several different technical principles, each of which has a different impact on the object's form. It is only in the case of simple objects, or ones made of a single material and whose functions only depend on geometric properties (e.g. a burin or shears) that a strong relationship between form and function can be found. And even then, the space for the design of different forms can be opened wide by introducing a simple question, such as how the tools are to be held.

designers from the old equivalence between form and esthetics. Thus form can be the vehicle of something else than beauty which Krippendorff called *meaning*. This new antinomy also brought its share of logical traps. *Why would function be meaningless per se?* If some form is meaningful, why can't we say that this meaning corresponds to a function, even different from any utility? We can even invert Krippendorff's proposition and claim that it is function as a *signified* value and not form as *a signifier* which is meaningful! Let's take the example of a chair made with a visibly recycled material. The recycled material being recognizable as such (an element of form) signals that the chair complies with sustainable development requirements as a *functional performance*. Thus, form may convey meaning *because* it signals a function explicit or latent (Almquist and Lupton 2010). Moreover, confusion can be easily created by opposing meaning and function. After claiming that "form relates to meaning", (Krippendorff 1989) suggests (p.16) "*four essentially different contexts in which objects may mean in different ways*". These contexts are: *operational, sociolinguistic, genesis, ecology*. They can be seen as functional domains where Krippendorff advocated paradoxically, that form should follow function. Thus the claim that "form not function is related to meaning" that was built against the modernist "form follows function" can also be interpreted as a neo-modernism that calls "meaning" the new list of functions that it advocates.

c) Finally, *what is the status of 'form'*? In spite of its self-evidence for industrial design[8], the notion of form has been shaken up completely by contemporary objects: what is 'form' when working on light, odour, texture, video or interactive software? It is no longer a metaphor of geometry or shape. If most modern objects do not have a 'form' in the traditional sense, they can be approached, like functions, through multiple and renewable *formal systems or semiotic ideologies (*Keane 2008*)* that are also related to *values, symbols and languages* that industrial designers use to design them. These remarks lead to a simple conclusion: function, form and meaning are too equivocal and too overlapping to provide a design theory or an ontology of design.

In this paper, we attempt to think about Design independently from these notions and to *distinguish industrial design from other types of Design*. We will bear upon recent advances in Design theory coming from the field of engineering design and our research endavours to cross-fertilize the literature in industrial design with the literature in Engineering design.

## Part I. Design theory: a common ontology for architects, engineers and industrial designers

The idea to define "*design"* without referring to *who* designs and to *what* is designed is not new. Herbert Simon formulated such program but he embedded design theory in the universal claims of the new science of decision. This led him to mistakenly conclude that design could be reduced to problem-solving methods (Hatchuel 2003, Dorst 2006). In the engineering design literature recent research rejected the assumption that design could be reduced to classic reasoning (Hatchuel et al. 2011, Hatchuel and Weil 2001, 2003). In addition, its findings are independent of any engineering domain or criteria and provide a theoretical perspective on design that clarifies its specific *cognitive* and *logical* issues.

### Design: generating the unknown from the known

[8] At the Bauhaus, Vassily Kandisky or Paul klee were considered as "Masters of form" (Droste )

Actually, this literature builds on a simple yet often underestimated fact. The aim of design is to create a 'thing' that is *not totally part of the existing knowledge* of either the designer or the persons to whom it is destined. Following Hatchuel and Weil (Hatchuel and Weil 2003, 2009) this fact has major implications: design is a unique activity which *generates* objects that:

- are unknown before design begins, or *design is reduced to copy.*
- are not obtained by deduction, induction or abduction, or *design is reduced to logic*.
- are not the discovery of pre-existing phenomena or *design is reduced to science or observation.*
- are expected to possess some desired properties that were formulated *before* design begins or *design is reduced to random idea emergence*.

If we combine all these features, design appears *as a specific type of rationality* [9] and contemporary design theory has elaborated new analytical notions that aim to capture this rationality, with a high level of generality. In the following, we introduce some notions from C-K theory (Hatchuel and Weil 2003, 2009), a good representative of recent currents in engineering design, that we will use to define Design in general and to understand industrial design as one of its forms[10].

**K-expansions, expansive partitions and expansive receptions**

The first step of C-K theory was to abandon classic terminology (function, form, technology, aesthetic, meaning…*)* and to define Design as the constructive interaction between *a desired unknown* (called a concept C) and available *knowledge* (called K). The major implications of this assumption is that design necessarily requires three types of *expansions* [11]:

- *Knowledge expansions (*also called K-expansions*)*: the designer has to expand her available knowledge; not only scientific truths but also social and psychological truths. This means that *pure creativity is not sufficient for design*.

- *Concept expansions* (also called C-expansions or e*xpansive partitions)*: these expansions are modifications of the *definitions (or identities)* of existing objects. It can be shown that at least one change of definition is needed in any genuine design task. These changes are obtained by assigning to existing objects *new attributes that were not part of their previous definition*. For instance, "tires without rubber", "bathrooms with a library" are "expansive partitions", because usual tires are all made with rubber and known bathrooms are not designed to store books. Such unexpected attributes attempt *to expand the identity* of *tires and bathrooms* and they open the generation of unknown possibilities for both of them.

- *Expansive receptions*: design presents to so-called "non-designers" (users, client or design students) objects that cannot fully be part of their knowledge (or no design is visible). Therefore the reception of design is itself an *expansive process* that may need learning, training, exploring, transforming… *From a theoretical point of view*, reception can be seen as a design process even if designers and clients, experience different capacities and social positions.

[9] The literature about "design thinking" has widely commented the specific features of design reasoning, but it has remained a broad narrative of a collection of practices that rarely reached the analytical rigour expected from an academic discourse (Dorst 2010)

[10] C-K theory is presented and discussed in more detail in the literature (Hatchuel and weil 2003, 2009 ; Ullah et al 2011)

[11] By "necessarily " we mean that these findings are consequences that can be formally established using logic.

## Reinterpreting metaphors and the creation of meaning

For sure, the design literature has widely described the role of analogies and metaphors for the generation of new ideas. However, the different type of expansions introduced by Design theory encompass these classic views an clarify the relations between design and the creation of meaning:
a) Metaphors can be seen as *special forms* of expansive partitions that occur in discourse. We know that they are traditionnaly defined as *tropes*, i.e. discourse figures by classic rhetoric. The notion of expansive partition is more universal; beyond text or speech, they can be embodied in any type of matter or media. Designers can build expansive partitions by drawing, mock-up making, or any physical transformations (for instance by assigning a fragrance to a piece of metal that usually smells nothing).
b) The link between metaphor and the creation of new meaning has been extensively studied (Ricoeur 2003). However, in design the creation of new meaning cannot be limited to a conceptual expansion. It depends of the whole design process by which *the identity of an object* can be modified and made *visible.* A main finding of C-K theory is that genuine design is creative and is possible *if, and only if, there is a combination of K-expansions and expansive partitions*. In simpler terms, design needs both discovery *and* creativity, observation *and* imagination, exploring the external world and changing internal lenses (or mindsets). These interactions create the seemingly chaotic appearance of a design process

## The dilemma of industrial design: immediately recognizable unknowns

Building on these findings helps to establish that, *due to different cognitive and social history*, design traditions do not organize *the path from knowns to unknowns* in the same way.

- *Engineers can be easily distinguished from the other two professions* because they draw on scientific discoveries and can mobilize important material and human ressources. They have also acquired the cognitive capacity and the social ability to propose *radical unknowns*[12]. Therefore, they can mobilize *expansions* at an extreme level (see table 1 for an illustration of levels of intensity). The first car, the first flying object and the first television were greeted with *astonishment, fear and amazement*! At the time, the commentators had to begin by explaining 'what they were' before they could comment on their value or on the exploit involved. As for their aesthetic, form and meaning, these questions always seemed anachronistic for truly unknown objects. Finally, the perceived social impact of engineering is such, that it is widely acceptable that citizens should learn some technology (or pay for learning) in order to be able to use their designs.

[12] This is not the day to day form of engineering in industry. However, engineering includes such radicality in its identity through direct links to science and technical dreams.

**Table 1 Intensity of expansions for each tradition[13]**

| | Architecture | Engineering | Industrial design |
|---|---|---|---|
| K-expansion | * | *** | * |
| Expansive partition | * | *** | *** |
| Expansive reception | ** | *** | * |

The path from knowns to radical unknowns is only exceptionally within the reach of architects or industrial designers. Both have to organize a more limited, less violent relationship between knowns and unknowns. Their capacity to operate K-expansions is limited. They cannot illustrate their exploits by exhibiting 'monsters', thus their 'unknowns' must simply be *attractive and surprising.*

- Industrial designers can finally be distinguished from architects. The latter have specific constraints stemming from the fact that their work is generally used by communities – families, inhabitants, citizens, etc. –. In addition, their designs are determined by social and technical norms and have a large impact on people's lives. This restricts the space of *acceptable unknowns in Architecture:* although there are examples of museums and theatres with surprising architecture, there are few buildings for housing whose purpose cannot be guessed at the very first glance. Industrial designers, on the other hand, can venture *much further afield*, sometimes even exploring unknown objects[14]. Nonetheless, they are subject to specific constraints in terms of *cognitive a*nd *value judgements*, which are a decisive factor. We are not talking about the usual constraints of cost, production and profitability because they apply to all design traditions. A demanding and core characteristic of industrial designers' work is that they must seek *originality (expansive partitions)* whilst also being *immediately comprehensible* by their potential clients. Jacob Jensen, the famous industrial designer from Bang&Olufsen talked about designing objects that were "*different but not strange*"[15], that arouse "*the power of making decisions without thinking*" in those receiving them. He added that the consumers always react quickly, in a simple trilogy: *"three seconds: fight, escape or love"*[16]. Industrial designers must therefore surprise or attract *under a tight social constraint*: *without the help of substantial explanations or special learning required from the consumer*[17].

We can now reformulate the problem of industrial design. Like all other design traditions, industrial design must organize the transition from knowns to unknowns. But, history has placed them in a specific position: they must produce an *unknown object that attracts and surprises, whilst being immediately or easily recognizable*. Our next step is to identify the type of design reasoning and social processes that are compatible with the "iron law" of industrial design: creating an unknown object that *attracts and surprises whilst never disconcerting.*

## Part 2. Industrial design: expanding and challenging the identity of objects

### About the identity of objects.

[13] The ratings are only illustrative. They should be interpreted not as quantitaive measures but as rank orders

[14] At the time this paper is written there is a design exhibition in Saint-Etienne (France) called "politique fiction" (politics fiction) presenting radically unknown objects.

[15] Raymond Loewy's MAYA principle (" most advanced, yet acceptable") is a close formulation of this dilemma even if its author never analysed it as a theoretical issue.

[16] All quotations of Jacob Jensen come from a plenary presentation at IPDM conference in Milano.

[17] Indeed, this constraint disappears for designed objects that will only exist in Museums or exhibitions, these institutions being precisely designed to organize such learning.

Let us examine what an *unknown yet recognizable* object could be. We need first to introduce the notion of "identity" of objects. Let us take the example of familiar objects such as 'chairs'. The history of industrial design is full of examples of *new chairs* that have been recognized as original creations. Yet, thee new chairs are still chairs, even if they present specific attributes that other chairs do not have. Hence, chairs have an identity that is both social and cognitive which can be maintained and recognized in spite of an infinite number of design variations. Designers therefore managed to obtain *expansions of the world of chairs*. Quite logically, some of the attributes retained to design the new chairs are therefore *expansive partition*s of the existing definitions of chairs. We must therefore look at the processes involved in producing expansive partitions which may also *convince and attract people*. Using the notion of object identity, we have only two options left to designers:

- *A process of adornment*: when the new object *keeps its identity* but is distinguished by a new value system.

- *A process of wit*: when *the object's identity is* questioned, made uncertain or in danger but *without being completely lost*.

Distinguishing between adornement and wit can be empirically tested at least from the reaction of users: in case of wit, most of them will express surprise and experience difficulties to designate the object. Yet, this distinction is absent in the literature about industrial design where the most common discussions where between Art and Design. Our main finding is that adornement and wit correspond to distinct intellectual traditions *that combine cognition and rhetoric* in different modes. Through such theoretical clarification the academic identity and analytical interpretation of industrial design can be made less obscure.

## II.1. Keeping identities: Adornment as an 'axiophany'

*How are objects given new value i.e. adorned?* By asking this question, we do not go back to the old controversies about ornament (Adolf Loos[18]), good design, style or fashion. Our task is to understand, with a high level of generality, how objects can *be adorned* i.e. can gain in value while keeping their identity. To advance on this point, we draw from the Hellenist Louis Gernet (Gernet 1968) who studied the formation of value in Ancient Greece. In this work, Gernet captured the long process that gave birth to currency as we know it today. He noted at the beginning of this process the presence of a class of objects that the Greeks called *agalmata*, from the verb *agallein*, meaning *to adorn, to honour*. Initially, *agalmata* were mainly precious objects and prizes won during games and offered to the gods as sacred gifts. Lavish generosity was both a widely popular sign of value and the process whereby the 'value' of the sacred gift *was made visible*. Some *agalmata* were also associated with legends (the Golden Fleece is one of the best known examples) in which they tend to evolve, although they preserve their original value. During this process, the value is transferred to those who are *adorned,* so to speak, by holding the objects[19].

[18] Adolf Loos 's famous paper "Ornament as Crime" appeared first in 1910.

[19] Translator's note: In French, agalmata is translated as parure, from the Latin paro, to prepare, honour and dress. Parure is used in modern French for costumes, finery and sets of jewels (as in English in the latter case), etc. The French verb "parer" is more common, with the same roots and meaning as the English 'to prepare'; it also means 'arrangement' and 'embellishment', as in the English translation we have used here, 'adornment'. The word apparence ('appearance' in English) has the same roots.

**Expansion and revelation of value**

Gernet's study provides precious insights into the mechanisms of *adornment*. First of all, it consists in imposing *an expansive value* to the adorned object; this value stems from *a legitimate and unexpected* source and is conferred on the object through a specific transformation. The process of adornment provokes a change in the object, making it larger, *illuminated*.

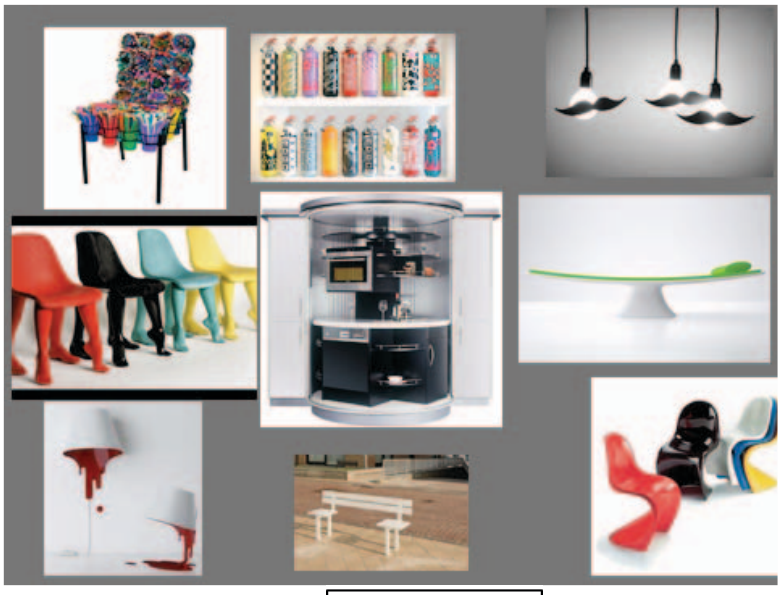

Fig 1

At the same time, a reverse phenomenon occurs: *an intrinsic value of the object is revealed* made *visible* by the adornment. The awarding of prizes or medals brings about the same process of distinction and revelation of a person. Through adornment, lamps, chairs, refrigerators, bathrooms, or any common object become unlimited potentials of value and seduction. It provokes *a transformative expansion* of an object that creates the attractive and surprising power of Design. However, it is crucial to understand that from our theoretical perspective the operation *of 'adornment' is not specific to aesthetic values: it should not be confused with ornament!* It applies *to any transformation, whether technical or social*, that infuses a particular system of new values to a known object *without changing its identity*. Ergonomics, friendly interfaces should be seen as adornments. Adornment generates an expansion by incorporating new value. This definition can be summed up in a neologism by saying that adornment is an '*axiophany'* as it brings to light (from the Greek "phanestai" and "axio "). In Fig.1 we present examples of designed objects that illustrate various types of adornment. The reader can check that all objects can be named even if they present surprising attributes (in the left lower corner, the reader may hesitate to see lamps, but this is a bias of the picture).

**Adornment as classic rhetoric**

When working on 'adornment', industrial designers can draw from the huge pool of values that are legitimate - or seducing - in their particular time and society. For instance, they can use colour ranges that match the latest trends in aesthetics, materials that represent a high-tech universe or codes from the most socially dynamic worlds (games, images, leisure, etc.). They can also politically or socially *criticize* these trends with *provocative adornments* that signify their engagement. Adornment corresponds to the cognitive and social model of *ancient rhetoric* (Perelman 1982). This ancient discipline also aimed to seduce and convince by designing discourse that could be easily understood by an audience. Topics had to be kept as close as possible of common knowledge. However, through argument, style, and eloquence, new value (truth, smartness, authenticity...) could be given to any thesis. For sure,

industrial design is about things and systems and *not* texts. However, likewise rhetoric uses *tropes* (i.e. standard figures of discourse) designers can use *adornment transformations* that are recognizable and valued by their audience. Adornment corresponds to the dominant and popular view of design thinking (Dorst 2011). Yet, as mentioned earlier adornment is not only thinking and producing metaphors: objects are transformed by design and this needs an important effort of knowledge acquisition and creation (K-expansions). Designers have also to capture new values and new tastes, as a source of new potential adornments (Tomkinwise 2011). Actually, Adornment, like design, can fail: the worst case scenario would be when a process of adornment *depreciates the value of an object and makes its identity more confused.*

## II.2. Breaking identities: Wit as an ontophany

Designers can create a surprise by adding new values, but in case of adornment *the object itself is not reviewed or called into question*. To go beyond adornment, industrial designers need to *shake* the object's identity and cause some turmoil in the mind of the audience. However, such perturbation must not last too long as the constraint of being recognizable still holds true. Actually, it is not really a question of re-cognition. The receiver must make an effort to decipher the design output. By upsetting the identity of an object, designers aim to provoke a feeling of *discovery, of freedom, like suddenly stepping into a new world of objects*. Just as we used 'axiophany' to describe the process of adornment, we can describe this second logic as *ontophany*, i.e. a process that not only reveals new values but also *new interpretable beings*. Is this design or creation? Does it give to industrial designers the same status as artists? Actually, the need to be easily recognizable excludes *a free* artistic approach, which would make the objects too radically strange and unique. We must therefore define the type of reasoning that causes liberating turmoil but not nonsense. *This type of reasoning can be found in the tradition of "conceptist" rhetoric.*

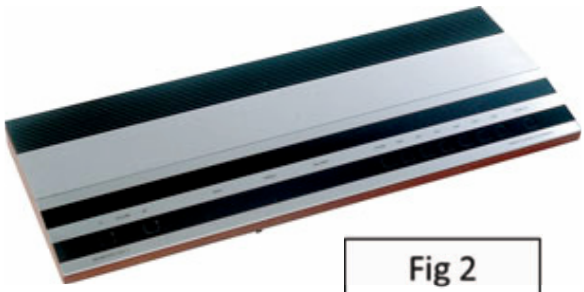

Fig 2

**"Searching for a conscious coincidence"**

Post-renaissance rhetoric was particularly interested in a type of figure called *wit*, which corresponds to the approach described above. The notion reached its peak with the Spanish exponents of 'conceptism'[20] in the 17th century. We refer in particular here to Baltazar Gracian's treatise, *Agudeza y arte de ingenio* [The Mind's Wit and Art], published in 1669[21]. It is most striking how close the propositions made in this treatise are to this second type of design. Gracian defined 'wit' (in Spanish *agudeza*) as "*a conceptual device, an original correspondence and agreeable correlation between two or three extreme contents expressed by understanding."* He also added that, by understanding the mechanism of wit, *the concept* can be defined as *"an act of understanding whereby one expresses the correspondence between objects."* Finally, this correspondence *"achieves the height of the artifice of ingenuity, and whether this acts by contraposition or by dissonance, it always represents an artificial connection between the objects."*

[20] Cf F. Villeurmier, « les conceptismes », P. Maffesoli « Histoire des rhétoriques en Europe ».
[21] Gracian also wrote several other treatises, including the famous *Courtier's Manual Oracle*, which gave him the reputation of being something of a 'Spanish Machiavelli'.

Gracian gives an actionable, rigorous definition of *concepts*, which interestingly can be used to analyze industrial designers' practices and discourse when they question the identity of objects. For Gracian, *wit*, the technique that builds concepts, is formed by bringing together elements that are spread far apart or found in *extreme* positions. They can be brought together in many different ways, for instance by forming an oxymoron or by introducing dissonance, or with the emergence of new harmony. Gracian's treatise is an impressive list of procedures for forming wit. Above all, its very profusion shows that wit albeit being a sophisticated system of thought, is one of its most natural forms and can reach its audience[22]. The aim of wit is, however, to take advantage of the *undefined elements* that always exist in known 'objects'. It is in the *voids or holes of knowledge* (Hatchuel, Le Masson and Weil 2012), that new, surprising, unknown things can be generated. Once again, we can quote Jacob Jensen[23] who defined industrial design work as *"the search for a conscious coincidence."* The wording is so close to Gracian that we could think that it was taken from his works, except that we have good reasons to believe that Spanish conceptism is not really part of the Danish industrial designer's culture. His definition sheds precious light on the combination of *surprising sophistication and simplicity* that we could find in Bang & Olufsen's Hi-Fi systems designed by Jensen (Fig 2).

Fig 3

**The special reception of wit: the role of intermediaries**

The notion of wit defines the *specific system of invention and innovation* that is allowed to industrial design. Ye, wit needs a special form of rhetoric and exhibition. Because the identity of familiar objects has been shaken, *reception is necessarily an active expansion process*. Designed objects may need new names and their value can be interpreted in various ways. The public is invited to act as a critic or to look for guidance from recognized experts or design institutions (Councils, exhibitions, institutions). Yet, wit can also find directly its public as the identity of objects is shaken but not radically changed. Therefore, *design as wit is not Art*, but it needs a type of rhetoric and a social model close from the latter. In a recent comparison between Design and Art (Mc Donnell 2011), the authors find that artists describe their work with a special language: they speak of "alibi, conceit, and scaffolding" in the description of their work. These notions are close to Gracian's definition of wit. Nevertheless, wit does not claim *uniqueness and singularity*, as artists may do. Finally, through wit,industrial designers can put ordinary life into question, or challenge stereotypes and experiences, without special learnings and without leaving the industrial world.

[22] Translator's note: "Wit" is generally used in modern English to designate humour (wittiness, witticism), but the sense 'ingenuity', 'intelligence' and 'understanding' still occurs in expressions such as "have a wit to', "to have one's wits about one", "at a wits' end", etc.

[23] Doubtless the only industrial designer of commercial products to have had two retrospectives of his work at the MOMA in New York –

In the pictures shown in Fig 3, we have gathered several examples where 'wit' is easily recognized. Most of them are simple objects or machines[24]. The reader can check that they are both familiar and strange, that one is tempted to give them names by forming expansive partitions (a blue fancy motorbike, a "segbyke"). Of course, all these examples are of work by famous industrial designers. Nonetheless, this second model explains how industrial design can be present in an economy dominated by innovation and a cultural system where Art has no rules.

**Design as epiphany?**

Verganti (Verganti 2009) suggested viewing design as an "epiphany of technology". Is this adornment or wit, or both? The value of theoretical models is to generate more precise questions. What's made visible by design in Verganti's epiphany, the technology itself or a value of this technology (adornment)? And to what extent the technology itself is maintained or revised (wit) in the design process? Verganti's model may be more adapted to the situation of emerging technologies which do not correspond to any existing object. In such cases, authors (Gillier and Piat 2011) have found a tendency to quickly fixate a *presumed identity* to this technique by associating it to known objects and values: here, *epiphany would mean a process of adornment which hides the unknown behind the known*. The same authors suggest avoiding such fixation by exploring new surprising identities of the same technology. Here epiphany would correspond *to the introduction of wit in technical design*. By distinguishing adornment and wit, hence axiophany and ontophany, we gain analytical precision but we also remind that industrial design mixes two distinct models of cognition and rhetoric. There is no unique model for the creation of meaning in industrial design.

## Discussion and conclusion:

**A core notion: the identity of objects**

In this paper we have developed the proposition that industrial design builds on two different universal models of cognition and rhetoric. key to our analysis is the notion of "identity of objects" which is valued by adornment or expanded by wit. Thus the academic positioning of industrial design can be clarified and research in this field should be grounded on two complementary domains:

| Table A. | Adornment | Wit |
|---|---|---|
| Identity of objects | Maintained | Shaken, challenged |
| Process | Axiophany :Expanding and revealing value | Ontophany : expanding objects and values |
| rethoric | Classic (Greek-Roman) | Conceptist (Spanish) |
| Social model | Classic market audience | Experts and Intermediaries |

- *Design theory* that is independent of any professional tradition and that explains with sufficient abstraction and generality how design is possible, i.e. how unknown objects can be generated through knowledge and concept expansions.
- *An anthropological perspective* that analyses the *cognitive* and *social* constraints, as well as the different *models of rhetoric* that are activated by industrial design (see Table A).

[24] Except for the house with a roof like a plane or an arrow which we included here to illustrate that the notion of wit can also be found in architecture)

It may be surprising that we do not mention aesthetics, functionality, or smartness as domains of design research. Indeed such issues are worth studying in industrial Design schools but *they cannot define its academic identity.* Instead, our claim is that adornment and wit are fundamental cognitive and social phenomena that industrial design research can study with rigour and precision.

Fig 4

In practice, wit and adornment can appear in the same design reinforcing each other. The interplay between adornment and wit is particularly visible and legible in Louis Ghost's chair, designed by Philippe Starck, with a great commercial success (Fig.4). The classic 'grand style' form would have been a rather insipid adornment without the wit provided by the transparent materials, with their effect of dematerializing the object. A same analysis could be done on the celebrated Apple's first iPhone, where the new tactile screen was used both to create adornment (aesthetic purity) and to generate wit (no keyboards in a phone). However their interplay should not be understood as their confusion. They represent two clearly distinct cognitive and social processes.

**Further research**

For industrial design research, *the adornment-wit model* paves the way for new empirical investigations that will be presented in later papers. Are there types of objects where wit is more frequent and more acceptable? Is it true for high tech products with interactive features? Are luxury furniture and goods more conservative and dominated by adornment? Can we find wit in more common products? What is the contribution of wit to the vitality of industrial design in contemporary societies? What are the conditions of commercial success in each case? Do schools of design prepare equally their students to both logics? The work programme drawn up at the beginning of the article can therefore be based on solid theoretical and empirical grounds. Modern industrial design only seemed to be mysterious and to lack its own reasoning because we did not have a theoretical framework with which to study design activities. A second step was to relate this to the intellectual traditions of rhetoric. We hope to have shown that they provide a very powerful analytical and critical framework. This framework helps set industrial design research into an intellectual project of wide theoretical and cultural significance.

We may now return to the introductory question of Marc Augé: "*what is that meaning created by design"?* What we have learned is that industrial design is neither applied Art serving commercial purposes, nor an emotional and sensitive form of engineering. As a design activity in its own right, industrial design *deconstructs* the meaning of ordinary objects and *explores its transformation by adornment and wit*. In this context, it can rightfully claim its own research and teaching environment in line with the most demanding academic traditions.

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# Design theory at Bauhaus: teaching “splitting” knowledge

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**Le Masson, P., Hatchuel, A., and Weil, B. (2015)**. " Design Theory at Bauhaus: teaching "splittir knowledge." *Research in Engineering Design*, (accepted)

# Design Theory at Bauhaus: teaching "splitting" knowledge

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## Abstract

Recent advances in design theory help clarify the logic, forms and conditions of generativity. In particular, the formal model of forcing predicts that high-level generativity (so-called generic generativity) can only be reached if the knowledge structure meets the 'splitting condition'. We test this hypothesis for the case of Bauhaus (1919–1933), where we can expect strong generativity and where we have access to the structures of knowledge provided by teaching. We analyse teaching at Bauhaus by focusing on the courses of Itten and Klee. We show that these courses aimed to increase students' creative design capabilities by providing the students with methods of building a knowledge base with two critical features: 1) a knowledge structure that is characterized by *non-determinism* and *non-modularity* and 2) a design process that helps students progressively 'superimpose' languages on the object. From the results of the study, we confirm the hypothesis deduced from design theory; we reveal unexpected conditions on the knowledge structure required for generativity and show that the structure is different from the knowledge structure and design process of engineering systematic design; and show that the conditions required for generativity, which can appear as a limit on generativity, can also be positively interpreted. The example of Bauhaus shows that enabling a splitting condition is a powerful way to increase designers' generativity.

## Keywords:

Generativity, design theory, splitting condition, Bauhaus, industrial design

## Introduction

What is the logic of creative reasoning? Recent advances in design theory have provided answers to debates on the possibility of any logic of creation and have allowed the analysis, modelling, and even improvement of the generativity capacities of creative people. There are models of generativity (Hatchuel et al. 2011). They describe, for instance, generativity that involves mixing 'non-alignment'-based concepts (Taura et Nagai 2013), generativity that relies on duality inside the knowledge space (Shai et Reich 2004a; Shai et al. 2013), generativity that relies on closure spaces (Braha et Reich 2003), or generativity that involves adding to a concept attributes that break design rules (i.e., C-K expansion (Hatchuel et Weil 2009)).

Based on these models, design theories provide an enriched vocabulary for the creative 'outcome'; e.g., there are designed entities at the borders of different semantic fields (i.e., general design theory (Taura et Nagai 2013)), designed entities that fill in 'holes' (i.e., infused design (Shai et Reich 2004a; Shai et al. 2013)), and designed entities that create new identities and new definitions of things (i.e., C-K theory (Hatchuel et Weil 2009)). The models also provide enriched descriptions of *how* design unfolded to get these entities; e.g., knowledge provoking 'blending' (i.e., general design theory), the uncovering of 'holes' via duality (i.e., infused design), and the use expansive partitions (i.e., C-K theory).

The above works provide us with new approaches of creation and creative reasoning. In particular, the models predict that strong generativity (which we later call 'generic generativity') is associated to (and, more precisely, conditioned by) specific knowledge structures; i.e., the knowledge base has to follow a splitting condition. This proposition is counter-intuitive as we tend to rather consider that the only limits to generativity are cognitive fixations. Hence, the present paper addresses the issue of whether we can verify the splitting condition in design situations that are particularly generative. If the splitting condition is true, it should be, for instance, particularly visible in the case of so-called 'creative professions' like art and industrial design. We therefore ask: *Relying on design theories, can we characterize a type of generativity of industrial designers—specific 'effects'—and specific conditions acting on the knowledge structure that help achieve these effects?* We do not study all industrial designers and rather focus on industrial design schools because they are the places where industrial designers are educated (and thus provide favourable access to knowledge bases) and where a doctrine of what is industrial design, and particularly its logic of generativity, is discussed, practiced and diffused. We focus on one of the most famous industrial design schools, Bauhaus, for many the matrix of several industrial design schools of today.

How does Bauhaus relate to generativity? Indeed, teaching industrial design does not necessarily consist of increasing creative design capability as it can also involve teaching existing styles and processes (e.g., drawing and moulding). Bauhaus itself was from time to time assimilated in a new style (e.g., the functionalist style); one can be tempted to think that the school actually taught this functionalist style. We therefore first clarify whether Bauhaus teaching really consists of teaching creative design methods (and theories) or only involves teaching a new 'style'. More generally, we will characterize the kind of creative expansion that Bauhaus teaching is expected to generate. We will show that Bauhaus actually aimed at a form of *style creation*, and we will show that this style creation can be characterized as a form of '*generic generativity*'. We will then uncover critical facets of the reasoning that leads to this 'generic generativity'. On the one hand, the creative craft of the

industrial designer is often viewed as a mysterious talent, reserved to those that are naturally born 'creative'(Weisberg 1992), and we will try to shed some light on this 'magical' talent. On the other hand, one might claim that the specificity of industrial designers is only a result of the type of knowledge industrial designers use (e.g., knowledge about users, ergonomics, symbolic meaning, sociology, culture, and form), and we will challenge the idea that industrial design is limited to certain areas of expertise. We will show that there is something more specific and more universal in Bauhaus teaching. Specifically, at Bauhaus, the capacity for design generativity is based on the acquisition of one very specific *knowledge structure*, characterized by two properties: non-determinism and non-modularity. We show that this knowledge structure corresponds surprisingly well to the so-called *splitting condition* in formal design models of mathematics.

Hence, we will characterize Bauhaus teaching as a way of helping students to be '*generically creative*' by building a knowledge structure that meets the *splitting condition*.

Finally, we show that this study of teaching in *industrial design* is also relevant to *engineeringdesign*. How can this be? Industrial design and engineering design are two clearly distinct traditions (see histories on engineering design (Heymann 2005; König 1999) and industrial design (Forty 1986) and the relationship between engineers and so-called 'artists' (Rice 1994)), two different professions, not taught in the same schools and embodying two different social roles. The contrasting figures of industrial design and engineering design use different journals, rely on different epistemologies, and connect to different disciplines. Still, engineering design and industrial design today share common interests. Design research societies try to bring them together through joint conferences. Both communities share today a concern about creative design and innovative design capabilities. Furthermore, recent progress in design theory has helped uncover the universality of design beyond professional traditions (Le Masson, Dorst et Subrahmanian 2013) (see also recent keynotes on design theory at the International Conference on Engineering Design 2015, Milan, and at the European Academy of Design, Paris 2015), thus supporting scientific exchanges between communities. The present paper aims at contributing to this trend. Specifically, by relying on Bauhaus teaching and design theory, we expect to learn about not only industrial design but also the relationship between industrial design and engineering design and, more generally, we expect to enhance our understanding of innovative design capabilities and critical aspects of design theory.

We briefly review the literature on generative processes to formulate our research hypotheses (part 1), before presenting our method (part 2), our analysis of Bauhaus teaching, compared with engineering design (part 3), and our research results (part 4).

# Part 1: The logic of generativity and its formal conditions

## *Generativity as a unique feature of an ontology of design*

Works on design theory in recent decades have revealed that generativity is a critical, even unique, feature of design theory; see, in particular, the 2013 special issue on design theory published under *Research in Engineering Design*(Le Masson, Dorst et Subrahmanian 2013). This logic of generativity was analysed both from an historical perspective (Le Masson et Weil 2013; Le Masson, Hatchuel et Weil 2011) and from a formal perspective (Hatchuel, Weil et Le Masson 2013). It was shown that design theory is dealing with the emergence of new entities, previously unknown but designed by relying on known attributes; i.e., it

addresses how to model the emergence of the new, the unknown, from the known. Different design theories proposed more or less generative models, relying on the specific language of the theory. As an historical example, one of the first design theories developed for machine design was the theory of ratios, developed by Ferdinand Redtenbacher (Redtenbacher 1852; König 1999). This theory is based on the language of each machine type (e.g., hydraulic wheels or a steam locomotive) and the generativity is thus limited to the machines described by the kind of language (e.g., the theory helps to generate previously unknown hydraulic wheels but cannot generate a turbine). Design theories have progressively increased their generative capacities by relying on abstract languages (or more precisely: on the abstract languages provided by the scientific advances of their time); e.g., general design theory relies on functions and attributes (Tomiyama et Yoshikawa 1986; Yoshikawa 1981; Reich 1995), the coupled design process overcomes the limits of functions by enabling the emergence of new functions (Braha et Reich 2003), infused design relies on duality in knowledge structures (Shai et Reich 2004a, b), and C-K theory relies on the logical status of propositions (Hatchuel et Weil 2009).

*Generativity and creativity—towards a variety of forms of generativity*

The different models highlight an overlooked area of research on creation and creativity: creative reasoning logic. Since the 1950s, psychologists have proposed measures of the effect of creative capacities (see Guilford criteria used to characterize a distribution of ideas—the fluency, diversity, originality of a set of ideas) (Guilford 1950). In the following years, many factors of creativity were identified (see Rhodes' 4Ps (person, process, press, products)) (Rhodes 1961). Still the reasoning logic of the creative mind has long remained out of scope. Several processes of creative reasoning have been proposed, all based on Wallas's model (information, incubation, illumination, verification)(Wallas 1926), itself already described by Poincaré (Poincaré 1908) (see also (Hadamard 1945)). In the 1990s, works on computer models of creativity were proposed. As underlined by (Boden 1999), they tended to distinguish between non-radical ideas, based on already known generative rules, and radically original ideas, which cannot 'be described and/or produced by the same set of generative rules as are other, familiar ideas' (p.40). Meanwhile, research in the field of psychology has underlined forms of 'bias' in creative design reasoning, leading to 'fixation effects' (Jansson et Smith 1991); i.e., distributions that are too narrow.

The above works focus on ideation and the psychology of ideation. Ideation is a part of design and often a phase in the design process. However, ideation does not account for all aspects of the generative process. In particular, ideation tends to rely on a 'closed-world assumption'; i.e., knowledge is given at the beginning of the ideation process. Hence, ideation cannot account for the generation of knowledge in design. Another limit is linked to the notion of an idea. Ideation focuses on the originality of one idea compared with other ideas, while generativity also accounts for the transformation induced by a designed entity; e.g., a newly designed entity might require/allow the re-ordering of the whole set of existing entities (i.e., new combinations between the new and the old are made possible and are accounted for by generativity). For instance, when Watt and Boulton designed a way to transform the parallel motion of the steam engine into a rotary motion, their design paved the way to new machines having several applications.

This discussion underlines that there are several forms and facets of generativity—beyond the quantity and originality of ideas. Generativity can also be characterized by knowledge creation and knowledge reordering induced by design.

## *Forms of generativity: 'generic' vs 'frequency' generativity*

Research that uses formal models helps uncover the variety of forms of generativity. The presentation of all these forms is beyond the scope of this paper. We discuss one of the most generative forms: generativity formalized by forcing.

Forcing is a method invented by Paul Cohen to create new models of sets (Cohen 2002, 1966)[1]. Cohen presented forcing as a generalization of extension techniques (e.g., the creation of a field of complex numbers from fields of real numbers) or a generalization of the Cantor diagonal method (e.g., the creation of new reals). This generalization is powerful because sets are basic mathematical structures on which it is possible to reconstruct all mathematical objects (e.g., numbers, functions, geometry, algebra, and topological structures) (Dehornoy 2010) – hence the genericity of forcing. As shown by Hatchuel et al. (2013), forcing can be interpreted as a generic *design* method. Of course, its validity is limited to the design of new models of sets (while preserving some basis rules of sets (basically Zermello Fraenkel axioms)), but set theory is so general that it is possible to establish correspondences between the design of models of sets and the design of other entities, as shown by the correspondence between forcing and C-K theory (Hatchuel, Weil et Le Masson 2013).

Without going into every mathematical detail, let's underline a first main lesson from forcing: its generativity.

The logic of forcing is as follows (see (Cohen 2002; Jech 2002; Hatchuel, Weil et Le Masson 2013)).

1) The first element of forcing is a so-called ground model M: a well formed collection of sets that is a model of the axiomatic of set theory, ie it follows Zermelo-Fraenkel axioms.

*Illustration*: this corresponds to the 'knowledge base' of the designer (e.g., knowledge of 'furniture'). As explained by (Dehornoy 2010), the logic of set theory roughly correspond to the intuition we can have on objects and sets of objects.

2) The second element is the set of so-called forcing 'constraints'[2] built on M. To build new sets from M, we have to extract elements according to constraints that can be defined in M. Let us denote by (Q, <) a set of constraints Q and a partial order relation < on Q. This partially ordered set (Q, <) is completely defined in M. Illustration: a piece of furniture has a shape, can meet functional requirements, and is made of materials. These are the 'constraints'. From Q, we can extract constraints that can form series of compatible and increasingly refined constraints ($q_0$, $q_1$, $q_2$ ... $q_i$), where for any i, $q_i < q_{i-1}$; this means that each constraint $q_i$ refines the preceding constraint $q_{i-1}$. The result of each constraint is a subset of M. Hence, the series ($q_i$) builds series of nested sets, each one

[1]As suggested by an anonymous reviewer (whom we warmly thank), we provide here complementary references on forcing – these sources explore forcing historically:(Kanamori 2008; Moore 1988); the reader can also refer to (Chow 2009). (Dickman 2013) is a case study of creativity in science applied to the discovery of Forcing.

[2] In forcing theory, one uses interchangeably the terms "forcing constraint" and "forcing condition". In this paper, we favor the term "forcing constraint" to avoid confusion with the "splitting condition" that will be presented below.

being included in its preceding set of the series. Such a series of constraints generates a filter F acting on Q. A filter can be interpreted as a step-by-step definition of some object of M. Q is the *knowledgestructure* used by the designer. Illustration: to define a certain piece of furniture, the designer can, for instance, describe the function, *then* the shape, then the materials (and hence there is a series of constraints that refine each other).

*Illustration*: in the world of industrial design, Q can have colour, texture, and be made of certain matter. In the world of engineering design, one would speak of functions, technologies, and organs.

3) The third element of forcing is the dense subsets of (Q, <). A dense subset D of Q is a set of conditions so that any condition in Q can be refined by at least one condition belonging to this dense subset. One property of dense subsets is that they contain very long (almost 'complete') definitions of things (or sets) on M, because each condition in Q, whatever its 'length', can always be refined by a condition in D. Still, a dense subset contains only constraints so that it is a way to speak of all elements without 'having' one element and speaking of them only in terms of their 'properties'.

*Illustration*: in art, the notion of the 'balance' of the composition of a piece of art could be interpreted as a dense subset defined by conditions such as lines, colours, and masses. The set of conditions leading to a balance is dense in the set of all conditions because, whatever a sequence of conditions (a partially defined piece), it is always possible to identify additional conditions with which to speak of the 'balance' of this partially defined object. In engineering design, usual 'integrative' dimensions such as cost or weight, energy consumption or reliability can be considered as dense subsets. Whatever the level of definition of the machine at stake, there will always be a constraint that refines this level of definition and is related to, for instance, cost (or energy consumption, reliability, and so on). For instance, the issue of cost can be discussed when only functional constraints are added or it can be discussed much later in the design process when a detailed design is produced.

4) The fourth element (and core idea) of forcing is the formation of a generic filter G, made of constraints of Q (hence from M), which step by step completely defines a new set. The exciting result of forcing is that, under certain conditions to be explained below, this new set defined by G is *not* in M. How is it possible to jump out of the box M? Forcing uses a very general technique in that it creates an object that has a property that no other object of M can have. Technically, a generic filter is defined as a filter that intersects all dense subsets. In general (see condition 1 below), this generic filter defines a new set that is not in M but is still defined by conditions from Q, defined on M. We can interpret G as a collector of all information available in M in order to create something new not in M.

*Illustration*: in the case of industrial or engineering design, a new piece is only a filter (a series of constraints (i.e., lines, colours, and material), functions, technologies, organs, and dimensions). There is no guarantee that a series of constraints builds a generic filter; i.e., there is no guarantee that the series intersects all dense subsets and follows condition 1 below. There is thus no guarantee that the new piece is 'out-of-the-box'. However, conversely, as soon as the series meets condition 1 and intersects all dense subsets, one

designs a new object that is made from the known constraints and is different from all the known objects.

5) The fifth element of forcing is the construction method for the extended model N. The new set G is used as the foundation stone for the generation of new sets combining systematically G with other sets of M (usually denoted M(G)). The union of M and M(G) is the extension model N.

*Illustration*: in the case of industrial design, a new object can embody a new style, and this new style can be used to redesign the whole set of known products, services, fonts and so on. A known example is the 'streamline' style that was used to redesign all kinds of products in the 1920s and 1930s (from aircraft to buildings, hairdryers, toasters and advertisement typography) (Engler et Lichtenstein 1990). In the case of engineering design, the development of a new machine is not supposed to lead to a revisit and redesign of the whole range of machines. Still, this can happen for so-called generic technologies; e.g., the development of electric motors and digital control systems led to the redesign of many systems and machine tools.

This leads us to the first powerful result of the mathematical model: *it enables us to characterize 'generic' generativity.* Let's explain this first point. Forcing creates a new set G that is built on M, and is, in general, different from all elements of M and is still coherent with the rules of M. Therefore, this set G is precisely 'generically' generative in that it is different from all elements of M but coherent and able to lead to the design of a whole collection of new entities, M(G). This 'generic generativity' can be distinguished from another type of generativity. Suppose that one distinguishes in M the elements made only with 'usual' constraints and the elements made with at least one 'original' (i.e., rarely used) constraint. The latter constraints might be said to be creative in the sense that they are original, since they use a 'rarely used constraints'. However, these elements *are in M*. This is a form of 'frequency' generativity, which is non-generic. Note that an 'exploration' logic in a complex search space leads to 'frequency' generativity; i.e., the new solution will rely on a rarely used routine (constraint) but this solution is still in the initial space of potential solutions.

If the set is in M, then the 'composition' (union, intersection, and so on of all operations allowed by Zermelo–Fraenkel axioms) of this set with sets of M is still in M; i.e., it is not 'new'. By contrast, if the set is not in M, then the composition of this 'new' set with sets of M is also a new set. Hence, there is the process of extending M to N = M(G). In summary, in the case of 'frequency' generativity, one stays in the box (i.e., the generativity is simply related to the fact that one uses an 'original', low-frequency constraint from the box M), and the new entity does not require the redesign of other entities. In the case of generic generativity, one uses constraints from the box M to go out of the box (G is not in M) and this leads to the design of all-new objects created from the combinations of the new entity G and the known entities in M.

This formal model clarifies two very different forms of generativity and leads to the first research hypothesis in our study of creative designers:

**H1: creative design aims at generic generativity**.

By contrast, designers who don't claim creative design rather rely on non-generic generativity.

## *Conditions of generativity: splitting condition and countable dense subsets*

Forcing models are a powerful form of generativity—a form that seems to correspond to phenomena of strong generativity, such as the design of a new style in industrial design, the design of a generic technology in the realm of technical objects, or even the design (discovery) of new scientific principles in the realm of science (see the emergence of relativity theory or quantum theory in physics for instance).

Forcing also clarifies some conditions of this generativity. Note that this is not intuitive in that one tends to consider that there are only psychological limits to generativity, such as fixations. Forcing theory provides us with a characterization of the formal conditions associated to generic generativity. In technical terms, forcing clarifies the conditions required for a filter to be a generic filter that goes out of M.

There are two conditions sufficient to create a 'generic filter': the splitting condition and countability condition.

*Condition 1: splitting condition (necessary condition)*

A generic filter does not necessarily go out of M. It has been shown that G is not in M as soon as Q follows the splitting condition; i.e., for every constraint *p*, there are two constraints *q* and *q'* that refine *p* but are incompatible (where the term 'incompatible' means that there is no constraint that refines *q* and *q*'). [3]

This formal expression corresponds to deep and general properties of the knowledge base of a designer (where we remember that M can be assimilated to the knowledge base of a designer and Q to the structure of this knowledge base). Let's clarify what the splitting condition means. It is easier to understand what a non-splitting knowledge base is. A knowledge base is non-splitting in two cases.

1—Deterministic rule: the knowledge base is non-splitting if there is one constraint *p* such that there is only one single series of constraints $q_1$, $q_2$… that refines *p* (see figure 1). This means that *p* determines immediately the set of constraints that follows. *p* is a deterministic rule that determines the entity. If there is such a deterministic rule, then the generic filter that contains *p* does not go out of M.

This kind of deterministic rule can be found when the designer relies on one specific know-how or considers that he or she applies scientific rules and principles. In both cases, the designer follows a unique predefined series of constraints after *p*. As a consequence, design can be generically generative only if the designer does not only rely on know-how.

2—Modularity: the knowledge base is non-splitting if there is one constraint p such that there are refinements q and q' of p such that there is a constraint r that refines q and q'. This means that q and q' are modules that can be added to the entity without making any difference to the following constraint r. r is insensitive to the choice between q and q'. q and q' are modular; i.e., they are interchangeable.

This kind of modularity can be found when the designer relies on building blocks that are interchangeable, such as Lego blocks. As a consequence, design can be generically generative only if the designer is not relying only on building blocks.

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[3]Demonstration (see (Jech 2002), exercise 14.6, p. 223): Suppose that G is in M and consider D = Q \ G. For any p in Q, the splitting condition implies that there are q and q' that refine p and are incompatible; one of the two is therefore not in G andthus is in D. Hence, any condition of Q is refined by an element of D. Hence, D is dense. Therefore, G is not generic.

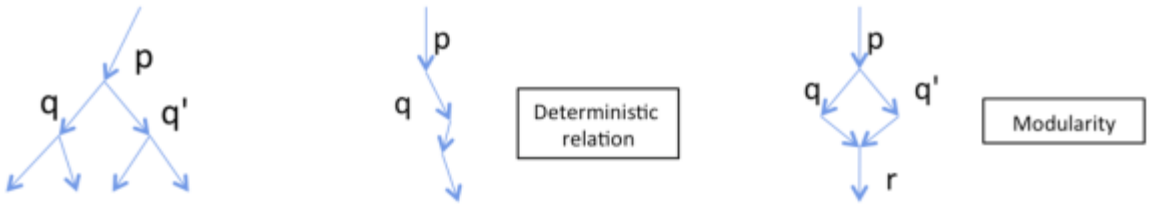


**Figure 1: Splitting condition**—left: constraints that follow the splitting condition; middle: a deterministic constraint p (non-splitting knowledge base); right: q and q′ are interchangeable modules (non-splitting knowledge base)

As a consequence, generic generativity can be obtained only with a knowledge structure without determinism and modularity. Conversely, a knowledge structure with determinism and modularity prevents generic generativity. Hence, this formal model provides us with a clear hypothesis with which to analyse creative design:

**H2: creative designers (aiming at generic generativity) will rely on a splitting knowledge base.**

Conversely, in the case of non-generic generativity, the designer relies on a non-splitting knowledge base.

*Condition 2: countable condition (sufficient condition)*

How can one build a generic filter? There is no single way. However, there is an interesting sufficient condition: if M is countable, then the collection of dense subsets of M is countable and there exists a generic filter on Q (in fact, there exists a generic filter G for every $p^*$ of Q such that $p^*$ in is G) [4].

This second condition corresponds to a constructive procedure that creates a generic filter. Because the dense subsets of M are countable, they can be ordered $D_1$, $D_2$… Beginning at constraint $p_0$, the designer can always find a constraint in $D_1$ that refines $p_0$ (because $D_1$ is dense); he or she takes $p_1$ and can then always find a constraint $p_2$ in $D_2$ that refines $p_1$ (because $D_2$ is dense), and so on. The sequence of constraints creates a generic filter G. If the knowledge base initially met the splitting condition, then the filter is not in M. This means that the design process is determined by the dense subsets and the countability logic that allows the classification of the dense subsets.

By contrast, what is the design process associated with a knowledge structure that *does not* meet the splitting condition? It can be shown that the generic filter is determined by the conditions where there is determinism and modularity[5]. The design process in the

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[4]Demonstration (see (Jech 2002), p. 203): Let $D_1$, $D_2$… be the dense subsets of Q. Let $p_0 = p^*$, a constraint in Q. For each n, let $p_n$ be such that $p_n < p_{n-1}$ and $p_n$ is in $D_n$. The set $G = \{q \in P / q > p_n$ for some $n \in N\}$ is then a generic filter acting on Q and $p^*$ is in G.

[5]Demonstration: If Q is non-splitting, then there exists $p_0$ such that whatever q and q' are refining $p_0$, there is r such that r < q and r < q'. We show that if $p_0$ is in G, then G refines all conditions stronger than $p_0$. We want to show that, whatever $q < p_0$, there is r in G that refines q. To this end, we introduce $D_q$ = {p in Q / p is not refined by $p_0$ or p < q}. $D_q$ is dense: for every p in Q, either p is not refined by $p_0$ and it is in Dq or $p < p_0$; we know that $q < p_0$ and Q is non-splitting, and hence, there is r < p and r < q. $D_q$ is therefore dense. G therefore intersects $D_q$. Hence, for every q that refines $p_0$, there is an r in $D_q$. Moreover, we know that $p_0$ is in G, and hence, r in $D_q$ necessarily refines $p_0$. Therefore, every constraint stronger than

case of non-splitting conditions is not determined by the *dense subsets* but is structured by the *constraints where the knowledge base is non-splitting; i.e., where determinism and modularity begin.* One would then expect a design process based on constraints (deterministic or modular) in non-generic generativity and a process based on dense subsets in generic generativity.

Hence, the formal model provides a clear hypothesis with which to analyse creative design:

**H3: creative designers (aiming at generic generativity) can follow a design process defined by the order of the dense subsets.**

Conversely, in non-generic generativity, design will rely on constraints that are modular or deterministic.

# Part 2: Research questions and method

## *Research questions*

In brief, based on formal models of design like forcing, we formulate the following research hypotheses regarding creative design.

H1: creative design aims at generic generativity; i.e., the design of an entity that is not in the initial knowledge base and that requires the reordering of the knowledge base by including all combinations of the newly designed entity and the previously known entities.

H2: creative design relies on a splitting knowledge base to get generic generativity; hence, learning creative design should involve gaining the ability to create a splitting knowledge base.

H3: the creative design process can follow a design process defined by the order of the dense subsets; hence, learning creative design should involve ordering dense subsets.

Said differently, formal design theory predicts that there are conditions that need to be met to realize generic generativity. This is intriguing. To check these conditions, it is interesting to analyse expert designers who are famous for their generativity, so as to check that their generativity can be considered a form of generic generativity, and then to analyse whether their knowledge base meets the conditions predicted by formal design theory.

## *Methods—material and analytical framework*

To empirically study generic generativity and its conditions, we need an empirical situation where generic generativity is most likely (to check H1) and we need to be able to characterize the knowledge base of the designer. This second condition is particularly hard to meet; i.e., how can one access the designer's knowledge base? Our research method involves studying *courses* offered at design schools. The study of courses provides direct

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$p_0$ is refined by a constraint in G. Hence, every constraint stronger than $p_0$ is in G. Hence, G is determined by $p_0$. Note that the splitting condition is sufficient but not necessary. A non-splitting knowledge base Q can be used to create a generic filter G not in M, which is a consequence of the theorem above that states that G must "avoid" all $p_0$ where modularity or determinism begins.

access to the knowledge acquired by the designer at school and hence, specifically, the knowledge structure built to do his/her designer task.
We focus on courses offered at Bauhaus for two reasons. 1) Bauhaus is famous for its powerful generativity. Although it requires further investigation, there is a good chance that H1 holds true for Bauhaus designers. 2) Bauhaus is famous for its formal teaching, which provides us with an impressive corpus with which to study the knowledge structure and design processes invented by famous professors to meet the challenge of creative design.

*Material: Itten and Klee courses*

This paper does not address all aspects of Bauhaus teaching but focuses on the courses given by Klee and Itten. This corpus, often criticized to be too formal and 'scientific' to meet generativity challenges, will nevertheless provide strong elements for our research.

Itten (1888–1967) was invited by Walter Gropius to teach an introductory course at Bauhaus. Itten taught this course from 1919 to 1922 (i.e., the very first years of Bauhaus). He considered that 'imagination and creative ability must first of all be liberated and strengthened' and he proposed to do this by providing specific knowledge on the 'objective laws of form and colour', with the idea that it would 'help to strengthen a person's powers and to expand his creative gift' (Itten 1975). His theory of contrast had to 'open a new world to students'. His famous theory of colours intended to 'liberate the study of colours harmony from associations with forms' and to help discover 'expressive quality of the colours contrasts' (Itten 1961). Hence, this course will be particularly helpful for our study of the kind of knowledge structure that can improve generic generativity.

We can go one step further to sharpen our analysis. It is interesting to note that the idea of providing knowledge to improve design capability was not new. Vitruvius had already (in the first century) insisted on the necessity for architects to master a large corpus of knowledge (Vitruvius 1999). When Itten taught his courses, engineers in Germany learnt engineering design by learning machine elements and engineering sciences (Heymann 2005). Still, machine elements or engineering sciences are not necessarily seen as sources of generativity. What is the difference between the kind of knowledge and learning capacities as taught by Itten and the machine elements and engineering sciences as taught in German machine construction courses at the same time?

Klee (1879–1940) was invited by Itten and Gropius in 1921 to teach at Bauhaus, where he remained as a professor for 10 years. His course 'Contribution to a pictorial theory of form' is described by Herbert Read as 'the most complete presentation of the principles of design ever made by a modern artist' (p. 186) (Read 1959). As he explains in the retrospective of his course (lesson 10), 'any work is never a work that is, it is first of all a genesis, a work that becomes. Any work begins somewhere close to the motive and grows beyond the organs to become an organism. Construction, our goal here, is not beforehand but is developed from internal or external motives to become a whole' (Klee 2005) [our translation]. His intention is hence to teach a process that creates an organism, a whole, which unfolds step by step. With Klee, it is particularly relevant to study design processes leading to generic generativity.

Here again we can go one step further. We know of such design processes that ensure that a coherent whole will emerge step by step. For instance, systematic design(Pahl et al. 2007) prescribes to develop a product through four main steps (i.e., functional requirements, then conceptual design, embodiment design and detailed design). Again, such a process is not particularly well known for its creative aspects, or more precisely, its

capacity to break design rules. Hence, what is the difference between the Klee design process and a classical engineering design process?

*Sources*

To study the courses, we rely on primary sources (Gropius 1923, 1925; Itten 1975, 1961; Kandinsky 1975; Klee 1922, 2005, 1966) and secondary sources (Wick 2000; Whitford 1984; Droste 2002; Schwartz 1996; Campbell 1978; Friedewald 2011). Note that the quality of primary sources is excellent. In particular, Klee said he was stressed by teaching so he wrote in his notebooks all the details of his courses, including sketches made during courses.

*Analytical framework*

In each case, we first present the courses, as described by the teacher and confirmed by former students. We then analyse the design logic in teaching from two perspectives: i) how does the teaching process affect (or attempt to affect) the *knowledge structure* of the students, and can this knowledge structure be related to the splitting condition (in particular, we will have to identify the 'constraints' for Bauhaus students, and the structure of these constraints) and ii) how does the course help the student learn a *specific design process*, and is this specific design process related to the countability of dense subsets? (In particular, we will identify dense subsets for Bauhaus students and analyse how they relate to each other, so that they can be considered 'countable'.)

To analyse the evolution of knowledge structures and the design process implied by design courses, we coded with C-K design theory (Hatchuel et Weil 2009)several Itten and Klee exercises. The theory provides us with an analytical framework that we can use to follow knowledge expansion resulting from design courses. In each case, we coded in K the knowledge acquired during the past courses, and in C the terms of the exercise. We then coded the answers to the exercises (i.e., the answer given by students when available, or the answer given by the professor) and the associated knowledge examples.

## Part 3: H1: style creation and generic generativity at Bauhaus

Before analysing Bauhaus courses, we first need to discuss the logic of generic generativity at Bauhaus. We show that generic generativity at Bauhaus corresponds to a logic of teaching style creation. We establish this point in two steps. First, we review works on teaching in industrial design, showing that there has long been a tension between teaching style and teaching style creation, with style creation being a form of generic generativity. We then show how Bauhaus clearly took a position in favour of teaching style creation.

### *Tension between teaching style and teaching style creation*

When looking at aspects of the history of industrial design education, there are recurring tensions about what should be taught.

1) United States and Germany, early 20$^{th}$ century. At the end of the nineteenth century, countries such as Germany and the United States decided to deeply reform their teaching of fine art, in particular as a pragmatic consequence of the World Fairs where German and American products exhibited poor quality (e.g., see the reception of German products described by Reuleaux (Reuleaux 1877) and the poor reception of American applied arts at the 1889 Paris Exposition (Jaffee 2005)). This decision corresponded also to a

more utopian focus on 'art as an arena of social improvement' (Jaffee 2005) (p.41) and the use of applied art as a way to recreate culture and communities in an industrial era (Schwartz 1996).

The teaching of fine art was then reorganized to be more like that of the Art Institute of Chicago and its school (Jaffee 2005). Jaffee explains that the basis of the new teaching is twofold. On the one hand, a 'vigorous technical component' (e.g., ornamental design, woodcarving, frescoing, mosaicking and the use of stained glass) was added to the offering of traditional fine arts (e.g., drawing and anatomy), in a tendency to address 'all types of works of house decoration and industrial arts, including the "modern arts" of illustration and advertising'. On the other hand, the teaching tended to be based on scientific principles: 'many American educators believed that abstract laws or principles of arts existed which, once stabilized, would not only facilitate the production of art but raise it to a higher level' (Jaffee 2005) (p. 44). These principles ranged from Ross's works (Ross 1907) to develop a rational, scientific theory of the aesthetic of perception to Dow's principles of composition (Dow 1920).

For some professors like Sargent, a leading figure of design teaching at the University of Chicago Department of Arts, such a program could support the creation of new styles: 'after the war, said Sargent in 1918 (cited by Jaffee), the United States will have to depend upon its own resources more than in the past, not only for designers but also for *styles of design*'. These methods were rather principles for addressing a higher, well-established, scientifically grounded 'quality'. Hence, there was an ambiguity that industrial design teaching was not really addressing the creation of new styles but intended much more to teach students existing styles to enable them to improve product quality. As Jaffee concludes, the kind of teaching finally led to an extended vision of styles, as characterized in the famous book of Gardner, a former student of Sargent at University of Chicago, *Art through the ages*(Gardner 1936). Gardner presented a world panorama of styles, guided by the idea that 'it was the universal values in design that made it possible for art to have a history' and providing clear methods for their appreciation and understanding.

2) France, end of the 19$^{th}$ century. Some decades earlier, in 1877 the old French school Ecole Gratuite de Dessin et de Mathématiques (created in 1766) was renamed Ecole des Arts Décoratifs, to signify a new logic in teaching. The new director, Louvrier de Lajolais (director from 1877 to 1906) explained that the school did not aim to teach technical skills (which were taught at another school, the Conservatoire des Arts et Métiers) or teach academic bases (which were taught at the Ecole des Beaux Arts) but aimed at educating a new generation of artists who were to master a large scope of technical knowledge (involving, for example, textile, ceramic, wood, and metal), with increased capacity to adapt to new tastes and to provide original models to industry. From this perspective, teaching has to consider interior design as a whole, with a 'style unity' that includes painting decorating as well as interior architecture, furniture, and so on (Raynaud 2004).

How is it possible to build this style unity? As explained by Froissart-Pezone (2004), since the 1870s, style unity was based on the idea that there is 'a logical relationship that links material, function and form, structure and ornament, following the courses and theories of Eugene Viollet Leduc', who taught at the school in the 1850s and was the professor who taught many school professors at the end of the 19$^{th}$ century (e.g., Victor Rupricht-Robert, Eugène Train, Charles Genuys, and Hector Guimard) (Leniaud 1994). According to (Raynaud 2004; Froissart-Pezone 2004), this education program finally led, in the early 1900s and, above all, in the time following the First World War, to a large success

in that, in this period, the Ecole des Arts Décoratifs reached a peak, embodied by the art déco style, which was a unique style with well-identified standards. Hence, the school was able to invent and teach one new style.

3) Germany, mid-20th century. Some decades later, the tension between teaching style and teaching style creation was also at the heart of the debate that occurred at Ulm Hochschule für Gestaltung (Institute for Design) between the first director Max Bill and his successor Tomas Maldonado (Betts 1998). For Maldonado, 'Bill's venerable "good form" itself becomes just another design style among many'. Here again the idea was to avoid relying on past styles. Rejecting art-based heritage, Maldonado insisted on the capacity of the designer to 'coordinate in close collaboration with a large number of specialists, the most varied requirements of product fabrication and usage'(Maldonado 1960). Teaching had to be based on system analysis and new product management. Relying on Peirce semiotics and Max Bense teachings, the curriculum intended to 'replace cultural judgement (taste, beauty, morality) with more scientific evaluation criteria' (Betts 1998) (p.79). As Betts summarizes, Bill and his colleagues tried to 'develop a critical theory of modern consumer culture untainted by Madison Avenue machinations' (p. 80), they looked for a more "ethically-based critical semiotics" to address the relationship between people and (consumable) things'. For Bense, the issue was to 'follow the lead of the modern physicist who studies the "objective world" not by analysing its objects but rather its interactive semiotics effects' ((Bense 1956) cited by (Betts 1998) p. 79). Still, this could also be interpreted as an extension of the logic of style to the interaction between the object and its environment. At the end of the 1960s, 'even the supposedly anti-aesthetic ethos of functionalism had become just another supermarket style, as the Braun design story attested' (Betts 1998). Here again the tension between style teaching and teaching style creation was a critical issue.

Interestingly, the extension from style to meaning also directly led to the famous proposition of Klaus Krippendorff, who graduated as a diplom-designer from Ulm, that 'design is making sense of things' or is a creation of meaning (Krippendorff 1989). However, the paper of Krippendorff precisely exhibits the same tension. In the first part, Krippendorff insists on the design ambition to be a capacity to create meaning, whereas in the second part (from p. 16), meaning creation is reduced to a referential of contexts (i.e., operational context, sociolinguistic context, context of genesis, and ecological context) that an engineer would consider a good list of functional requirements.

These elements give us two insights into the issue of design teaching. First, over time, there was a progressive extension from the design of objects (e.g., domestic objects and applied-art pieces) to multiple objects (e.g., trademarks, advertisements, and shop windows) and to styles and meaning (e.g., new icons, symbols, signs, new forms of interaction between objects and people and even today 'semiotic ideologies' (Keane 2003)). A similar evolution can be seen in the historiography of design (Riccini 1998). Second, teaching styles (or meaning) are a source of tension between two approaches: teaching (past and new) styles and teaching the *creation* of style(s).

We can now better characterize this tension. Teaching past and new styles can be characterized as teaching the values (or what engineering would call 'the functional requirements') of existing styles and the ways and means to acquire them (e.g., mastering drawing, composition laws, and material techniques such as woodcarving, frescoing, mosaicking, and the use of stained glass), whereas style creation (or even 'meaning creation') consists of creating an original culture that encompasses new 'objects' as well as

new interactive receptions by people. Hence, a clear challenge for the new style is that it has to be 'significantly' original and new (i.e., removed from past styles) yet still has to be 'meaningful' to the (occasionally lay) 'user(s)', who should be able to 'make sense' of the new by relating it to the known. The new meaning is both *original* and strongly related to *all* of what is already known. The style has to be new and will affect very large types of artefacts (e.g., techniques, objects, environments, uses, individuals and social references). This is precisely a generic generativity—new on many facets and leading to revise a whole world of objects, uses, and ways of life.

## *Teaching style creation, a challenge at the roots of Bauhaus*

The tension between teaching style and teaching style creation was at the root of Bauhaus. This was illustrated by (Schwartz 1996) in his study of the German Werkbund, the melting pot of the debates that would later shift to Bauhaus. From the 1890s onwards, the members of the Kunstgewerbe Bewegung and later the Werkbund (500 people at the Werbund creation in 1907 and 2000 in 1914, among them Hermann Muthesius, Peter Behrens, Henry Van de Velde, Richard Riemerschmid, and Werner Sombart) launched wide discussions and initiatives on German applied arts[6]. They rejected the use of 'historical styles' (as used in Fachverbände, professional associations) and promoted the direct involvement of artists in the production of objects of everyday life, taking into account the industrial conditions of production and trade. The works of Peter Behrens at AEG illustrate the contrast between the 'historical style' approach and the Werkbund approach (see Figure 2 b). They also show that designers like Behrens not only coped with objects but with the complete environment (e.g., AEG trademarks, retail shop windows, product catalogues, and even the factory itself).

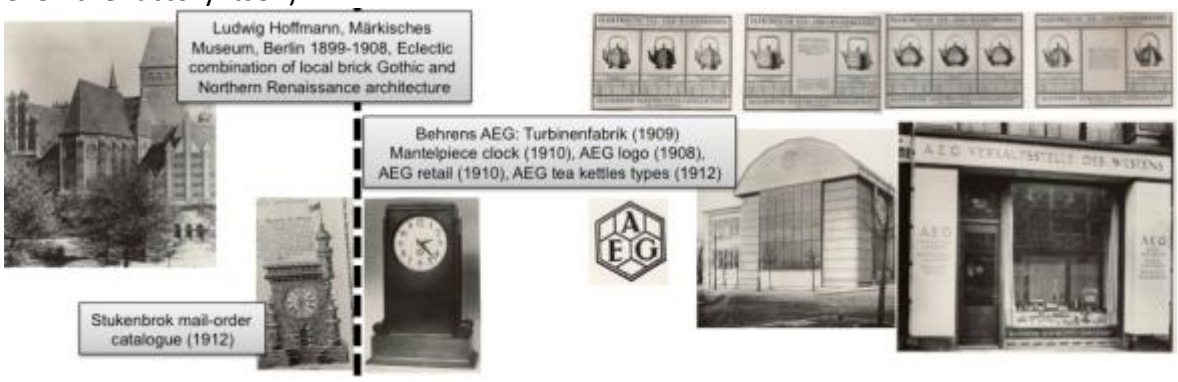


**Figure 2: 'Historical styles' vs Behrens works at AEG in the 1900s–1910s**. Left: one or multiple existing styles are used to design objects (a museum and a clock). Right: Behrens creates a new style coherent with many new objects (a clock, kettles, and new AEG domestic electric appliances) but also with a work environment (a factory), a retail environment (shop window) and a marketing environment (brands). (Source: adapted from (Schwartz 1996))

[6]They sponsored lectures, exhibitions (Köln 1914), and publications (Werkbund Jahrbücher), helped found a museum of applied arts and were involved in Dürerbund-Werkbund Genossenschaft (publishing a catalogue of exemplary mass-produced goods 1915), linked to Werkstättenbewegung (Riemerschmid, Naumann). In parallel, they made great effortsto establish a theoretical basis, and Werkbund was a forum for discussion, with a wide cultural, economic, social and political audience.

As shown by Schwartz (Schwartz 1996), one of the great issues facing Werkbund was to create 'the style of our age', the so-called 'Sachlichkeit'. Sachlichkeit was *not* the aesthetic payoff of the functional form (and functionalism as such was widely discussed and rejected in the Werkbund) but rather the avoidance of form as Fashion (see Muthesius, 1902, Loos, the ornament as crime, 1910; and Gropius 1923). Werkbund members remembered the story of Jugendstil: Van de Velde, Riemerschmid and others proposed a new style that was finally transformed into inconsistent fashionable ornaments (see Figure 3). In the social tensions created by the industrial revolutions in Germany, and following Tönnies works on the new Gemeinschaft (community) that counterbalanced the complexity of contemporary Gesellschaft (society) or Sombart on Kunstgewerbe and Kultur, they wanted to organize to create a new style; i.e., a new culture and new communities created through designed objects.

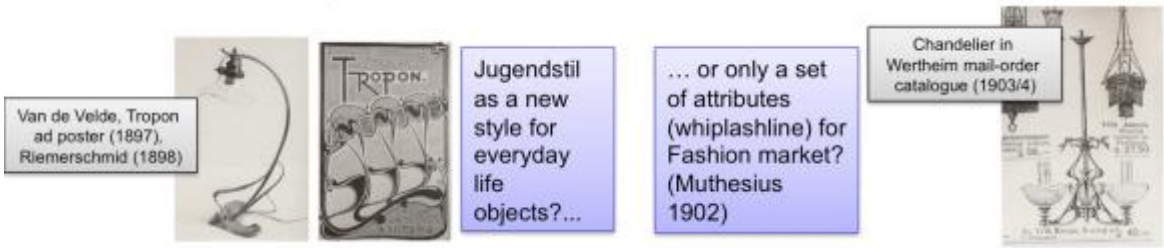


**Figure 3: Jugendstil—inventing a new style (left) or just a fashionable ornament (right)?** (Source: adapted from (Schwartz 1996))

Once again, this ambition was trapped by the debate between style and style creation. In 1914, the Werkbund was split between the Muthesius party of Typisierung arguing for the standardization of production and distribution of objects (protected by copyright) that would embody the new style (of the new society), and Van de Velde (supported among others by Gropius and Osthaus), who advocated a free capacity for designers to create their own 'style'.

Werkbund and the 1914 crisis laid the intellectual foundations of Bauhaus. 1) The designer should not subordinate himself to the law of any style, nor should he just make use of motifs (like the Jugendstil motifs) in designing fashionable products. 2) What has to be designed? Not a product, but a whole range of commodity products including trademarks, advertisement, shop windows, and catalogues so as to create the 'style of the age'. 3) This style creation is not reserved to a few happy designers protected by copyrights or standardized but should be made accessible to many designers through teaching.

In conclusion, we have established that Bauhaus aimed to convey to students a capacity of generic generativity. Bauhaus is thus a case in which creative design consists of generic generativity (H1).

We will also verify our methodological assumption. Because teaching is considered a way to convey this generic generativity capacity, the analysis of courses is critical in testing hypothesis H2 and H3. Does the knowledge structure promoted by Bauhaus courses correspond to the structure predicted by design theory?

## Part 4: Results: knowledge structure and design process for generic generativity (H2 and H3)

We now present the results of analysis of the Bauhaus courses. We analyse first the Itten course and then the Klee course. For each course, we give a brief description and analyse the

course according to design theory and present the results for H2 and H3 hypotheses. Finally, we underline the differences between the two courses and apparently similar courses in engineering design.

## *Itten: a 'contrast'-based knowledge structure that better opens holes*

**Brief description of the Itten course**

The Itten course is based on means of classical expression and has a chapter on each of lines and points, form, colour, material, and texture.

We focus on the chapter on texture as an example and analyse the series of exercises proposed by Itten to learn about textures (Itten 1975). In a first phase, students are told to draw a lemon. Beginning with the representation of an object, Itten wants the students to go from 'the geometrical problems of form' to the 'essence of the lemon in the drawing.' This is an 'unfixing' exercise, helping the students to avoid assimilating the object with a geometrical form.

In a second phase, the students are asked to touch several types of textures, to 'improve their tactile assessment, their sense of touch.' This is a learning phase in which students 'sharpen observation and enhance perception.' (Itten 1975)

In a third phase, students build 'texture montages in contrasting materials' (see figure 4). During this exercise, students begin to use textures as a means of design. The constraint (design only by contrasting textures) helps students learn about textures (i.e., to explore the contrasting dimensions of different textures and to improve their ability to distinguish between them). It also means that students are able to explore the intrinsic generative power of textures; i.e., the superimposition of textures that should create something new, such as 'roughly smooth', 'gaseous fibrous', 'dull shiny', and 'transparent opaque'. Moreover, students begin to learn the relationship between texture and a complete work, a composition, in contrast to the idea that texture could be secondary and 'optional', chosen independently of the rest of the piece. The exercise thus makes textures a critical part determining the whole.

**Figure 4: Texture montage exercise (source: (Itten 1975))**

The fourth phase could be qualified as 'research'. As the students are by then more sensitive to the variety of attributes of a texture, they can 'go out' to find 'rare textures in plants.' It is interesting to underline that Itten does *not* begin with this phase. He begins by strengthening the students' capacity to recognize new things, just as a botanical researcher has first to learn the plant classification system and to discriminate features before being able to identify a new specimen. In particular, students are told to find new textures for a given material (see the figure 5 in which all textures are made from the same wood). Once

again, this is an exercise of disentangling texture from other fixing facets (i.e., materials in this case). Note that, in this step, Itten does not teach a pre-formatted catalogue of textures but teaches the student how to learn textures, thereby building their personal 'palette'.

**Figure 5: Several textures of the same material (source: (Itten 1975))**

The fifth phase consists of representing textures. Itten stipulates that students have to represent 'by heart', 'from their personal sensation', to go from 'imitation' to 'interpretation'. Instead of being an exercise of objective 'representation', this exercise is intended as a design exercise, as students had to combine textures with their own personality. Just as phase 4 aims at creating something new from the superimposition of contrasting textures, the idea in this phase is that the new should emerge from the superimposition of texture and the individual 'heart'. The phase is also intended to help improve sensitivity.

The sixth and final phase consists of characterizing environmental phenomena as textures. For instance, the figure shows a marketplace painted as a patchwork blanket. Itten urges students to use texture as an autonomous means of expression and not to just produce a 'constrained' ornament. By combining their enriched algebra of textures and the algebra of scenes, students can create new 'textured scenes' that are more than the scenes and more than the textures. As Itten (Itten 1975) explains, 'It stimulates the students to detach themselves from the natural subject, and search for and reproduce new formal relations'.

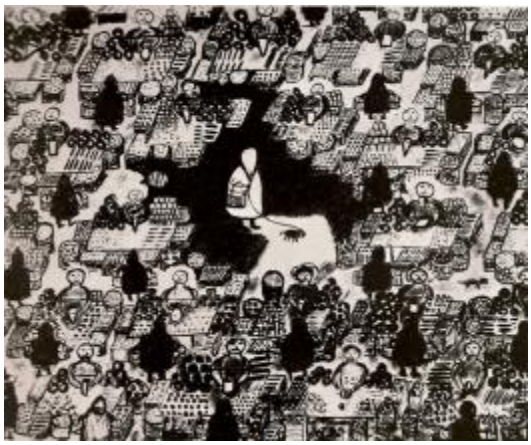

**Figure 6: Characterization of environmental phenomena as textures (source: (Itten 1975))**

We could repeat this analysis for other aspects of Itten's teaching (e.g., lines and points, form, and colour).

**Analysis of the Itten course from a design perspective**

We now turn to the analysis of the Itten course. We first need to underline one critical point: Itten does not teach a stabilized knowledge base (or a stabilized style associated to it) but rather teaches students how to build their own knowledge base (to create their own style). In all cases, one finds that Itten improves three facets of his students' design capabilities.

a- Self-evidently *students extend their knowledge base* for the notion of interest (e.g., texture), knowing more about (texture) materials, (texture) descriptive languages, (texture) perception, and (texture) building techniques. In terms of colour, Itten teaches to increase the student's capacity to perceive 'distinct differences between two compared effects' and to 'intensify or weaken (colour) effects by contrast'. In that sense, there is no great difference from an engineer learning machine elements, their production processes, and their functionalities; i.e., learning what design theorists would call design parameters and functional requirements. In both cases, seen from this perspective, the knowledge structure appears as a well-ordered catalogue of recipes. Still, the knowledge structure is a highly complex one, for which only a few combinations have been explored.

b- Students are ready to learn about the notion of interest. They know *parts of what they don't know*: the contrasts, the materials, the process, the perception and sensations they have tried to convey and those they could not try to convey involving unavailable materials, new combinations, and sharper sensations. As Itten writes, ' a theory of harmony does not tend to fetter the imagination but on the contrary provides a guide to discovery of new and different means of colour expression' (Itten 1961). The industrial design students know the limit of what they know and the way to learn beyond. They not only know the state of the (their) art but also the state of the non (yet) art. The knowledge structure is closer to that of a very smart scientist–engineer, who not only knows the engineering sciences but also know their limits and is ready to follow the advances they make.

   At this point, we can already underline that this knowledge structure *enables a designer to extend his or her own design rules*. It is closer to style creation than teaching the design parameters and functional requirements of pre-given styles.

c- Beyond rules and the learning of rules, students are able to deal originally with briefs or to give themselves original briefs. This is the key logic of contrasts. Itten does not teach colours, forms, and textures but teaches the contrast between colours, forms, and textures. The juxtaposition provokes surprise, it creates 'holes' in the knowledge base, which have to be explored by the designer. A contrast does not correspond to a unique meaning with a one-to-one correspondence but instead paves the way to multiple elaborations. With Itten, students learn to formulate exercises (briefs) that can be oriented to explore new textures, new texture montages, and new texture contrasts. These briefs can also be oriented towards creating original works using textures (or colours or forms) in a unique way. In that sense, the teaching of Itten is much closer to educating a senior scientist, who has not only to answer exogenous research questions but has also to be *able to construct his or her own, original, research program*.

Up to this point, we understand that Itten's teaching is sophisticated, much more than just teaching the elements of an existing style or teaching a new technique or relying on a kind of 'project-based learning'. We have now to clarify how this kind of teaching can help deal with generic generativity.

It should first be noted that, despite apparent knowledge expansion, the knowledge base relies on classical motives (e.g., drawing, colour, material, and texture). Therefore, if there is generativity, it is not based on the use of radically new means. At the time, there were transformations in expression means, and Bauhaus was aware of them. For instance, photography was considered an applied art, as evidenced by a book published by Meurer (Meurer 1896) and photographs published by Karl Blossfeldt (Stoots 2011; Blossfeldt et Nierendorf 1928). Bauhaus participated in this movement through the teachings and book of Moholy Nagy (Moholy-Nagy 1938). Bauhaus is also famous for the works done on new typography. However, Itten did not teach these new means and relied on a known set of means (e.g., textures and colours). Hence generativity won't come from new means but from the combination of known means.. Still, a combination is not necessarily creative and does not necessarily imply H2, that a knowledge base should meet the splitting condition. We therefore ask, *how does the knowledge base enabled by the Itten course meet the splitting condition?* To this end, we made an in-depth analysis of the design reasoning in Itten's exercises, to analyse how they lead to changes in the knowledge base of the students. We illustrate this analysis for one case, taken from the texture lesson (see figure 7).

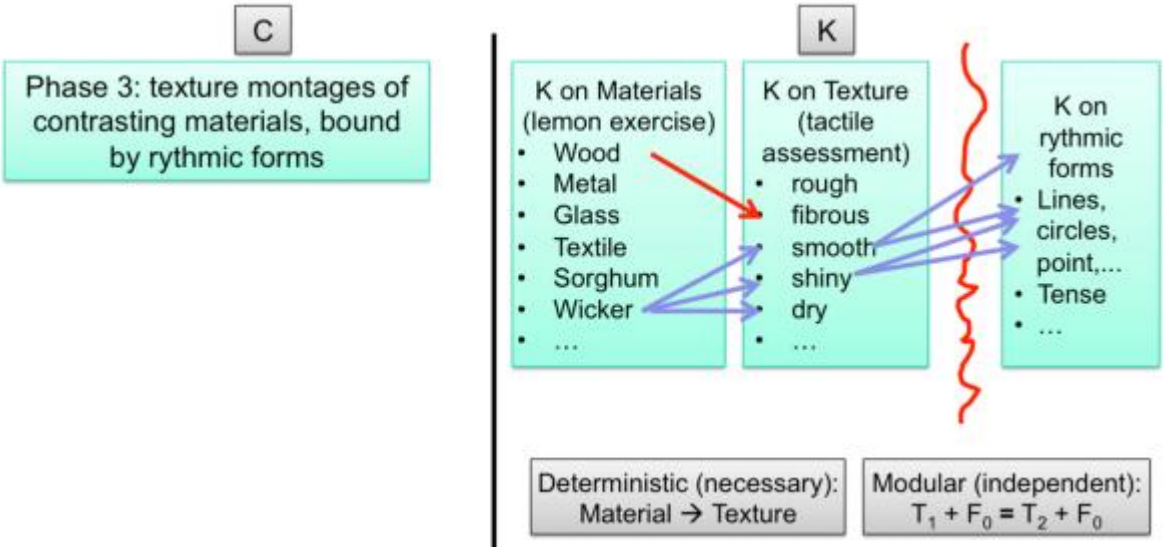


**Figure 7: C-K analysis of one Itten exercise ('texture montage')—initial state**

The exercise brief is given in C: 'texture montages of contrasting materials, bound by rhythmic forms'. In K, there is the knowledge acquired by students during the first courses, related to Itten's exercise: knowledge about materials, textures, and rhythmic forms.

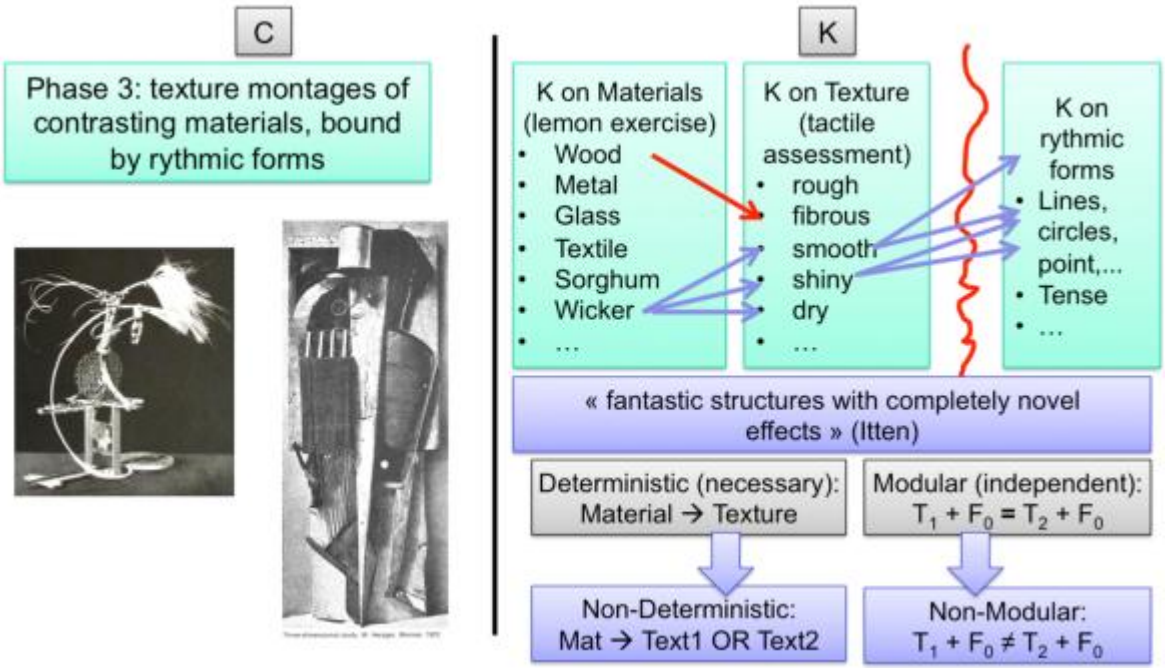


**Figure 8: C-K analysis of one Itten exercise ('texture montage')—final state (sources for the pictures: (Max Bronstein 1921))**

According to Itten, the exercise leads to 'fantastic structures with completely novel effects' (see two examples in the figure above), and hence a form of generativity ('fantastic') that might be said to be generic in the sense that it is not the structure but the 'effects' that are new. The exercise creates new effects and not only a new structure.

The consequence of the exercise on student's knowledge is summarized in K in the figure above. In this particular case, the expressions means (which correspond to the language of constraints in forcing) are unchanged. The exercise uses knowledge on materials, texture and forms gathered in the previous exercises (i.e., the lemon exercise, tactile assessment exercise and montage lesson). However, the *structure* of the relationship among them (which corresponds to the partial order of constraints in forcing) has strongly evolved. In the initial state, the relationship between material and texture is deterministic; e.g., wood implies fibrous texture. Additionally, the relationship between texture and form is modular, in that whatever the form, it is possible to add texture 1 or texture 2 without there being major changes to the final result. *After* the exercise, these two properties are changed. In the example, the material 'wicker' is related to shiny, smooth, and dry properties. Hence, the deterministic law is relaxed. Meanwhile, the form is made of and by textures, and it appears that there are new relationships between some textures and some form properties. A texture will reinforce slenderness or lightness or angularity. Therefore, a form with texture 1 will now differ from a form with texture 2.

In this particular case, one exercise leads to the revision of the relationship between expression means (i.e., a partial order of constraints), resulting in two specific properties of the knowledge base: non-determinism and non-modularity. C-K analysis of the other exercises confirms this transformation. The knowledge structure built through Itten teaching can be characterized by two properties.

- *Non-determinism:* when confronted by a concept, the student cannot use a deterministic law. Because of the variety of contrasts, there is no law that links one colour to one material to one texture to one effect. At each step, the designer can

always explore multiple paths. Itten fights against 'laws of harmony' or 'clichés' that tend to impose relations (e.g., warm fibrous wood or cold smooth shiny metal). He wrote in his book on colours that we should 'liberate the study of colours' harmony from associations with forms.' For instance, the 'cliché' deterministically associates wood with a fibrous property, while Itten's teaching opens the way to smooth wood, which will differentiate the designer's work from all previous work using wood as a fibrous material.

- *Non-independence:* not all attributes and not all combinations are equivalent. Itten does not advocate relativism. On the contrary, he states that 'subjective taste cannot suffice to all colour problems'. Relativism deletes the valued differences. If texture is only a 'secondary', 'modular' property, then all works with wood are similar; i.e., a work with smooth wood is indistinguishable from a work with fibrous wood. Against 'relativism', Itten teaches that one does not add a texture *independently* of the other aspects; if a scene or montage can be made of and by texture, then a scene or a sculpture is not 'insensitive' to the choice of texture. For Itten, each attribute (e.g., texture, colour, or material) affects the whole work and propagates to all other aspects. Here again, the notion of contrast is critical in that each juxtaposition is a source of meaningful contrast that has to be amplified, tamed, or counterbalanced by another.

In concluding Itten's teaching, we state that *non-determinism* and *non-independence* are two critical properties of the knowledge structure provided by Itten.

**As a consequence, H2 is confirmed for the Itten course—a splitting knowledge base is a condition for generic generativity.**

**Comment on the Itten course: similarities and differences with engineering design approaches**

Let's underline that the two properties stated above are much different from the logic of classical engineering design. Formally, we can associate the knowledge of expression means to machine elements (Kesselring 1942; Pahl et al. 2007; Reuleaux et Moll 1862; Bach 1896, 1924; Findeneisen 1950; Laudien 1931; Rötscher 1927) (these are 'constraints'); we can say that engineering design consists of combining machine elements just as industrial design consists of combining expression means, and we can associate the knowledge of the laws of contrast to engineering science (Rodenacker 1970; Hubka et Eder 1988; Dorst et Vermaas 2005), in the sense that some laws determine the design parameters to be used.

This comparison reveals strong differences in the structure of constraints.

1) *Modularity*: we have seen that Itten teaches the student to combine expression means in a *non-modular* way, with each expression means being in strong relationship with all previous means, amplifying and expanding them. By contrast, in engineering design, machine elements are *made to be modular*. For instance, machine elements that have to meet a similar set of requirements are substitutable; or it is possible to use one machine element for one functional domain, independently of the type of object or the type of user. As soon as there is a rotating rod, it is possible to use a ball bearing, be it for a car or a power plant.
2) *Determinism*: Itten teaches the laws of contrasts and the laws of colours, with the idea to show that there is *no determinism* and that there is a multiplicity of possibilities—there are seven types of contrasts and no rule that links colours in one single way. By contrast, engineering design tends to use laws to *determine*

design parameters. Employing scientific laws, it possible to use the set of requirements to determine the technology to be used. Ideally, it is expected that knowledge of engineering science will be rich and precise enough to immediately determine one object for each list of requirements.

These two contrasting structures of knowledge lead to contrasting forms of generativity. There is generativity in engineering (Lindemann 2010) that consists of, for instance, finding a new technique with which to address previously unmet requirements (e.g., energy harvesting in microelectronics would benefit from using energy dissipated by microprocessors). This generativity improves some aspects of the final design but keeps the others unchanged (e.g., the microprocessor with energy harvesting is a microprocessor that has one additional property in that, for instance, it still computes). It follows a modular logic and the knowledge base of the engineering designer remains non-splitting. As a consequence, the new object will be immediately compatible with other objects, without requiring the redesign of a whole set of entities.

By contrast, Itten's teaching enables students to build a splitting knowledge base. The newly designed entity will hence intersect all types of attributes. In the texture exercise, the creative effort finally implies material attributes (e.g., wood or wicker), texture attributes and form attributes. The newly designed entity paves the way to the redesign of complete sets of entities. Creating a new style, all existing objects could be redesigned with this new style.

Of course, as we will discuss in the conclusion, one can certainly find today design that is made by engineering and that is still generically creative, and conversely, we can certainly find design made by industrial designers that is not generically creative. Our result is not at the level of the professions but at the level of the structure of the knowledge base conveyed by Itten teaching and by machine elements and engineering science teaching.

In summary, Itten teaches students how to build their own knowledge base meeting the splitting condition (i.e., non-determinism and non-modularity). By contrast, classical engineering design enables students to build a knowledge base that is non-splitting.

## *B- Klee: composition as a genesis process, leading to out-of-the-box design*

### Brief description of the Klee course

We now study the Klee courses. We present three facets of the courses.

1- Even more so than Itten, Klee provides *an extended language of the design object*. Beginning with 'lines', Klee introduces the notions of the active (vs passive) line, free line, and line 'with a delay' (befristet in German) (see figure 9). After lines, Klee addresses notions such as the rhythm of a piece, the spine of the piece, the piece as a weighing scale, the form as movement, the kinetic equilibrium, the organs and the organism. In particular, Klee proposes new languages for perception, considered as a 'moved form' with specific kinetics, ranging from pasturage to predation (see figure 10).

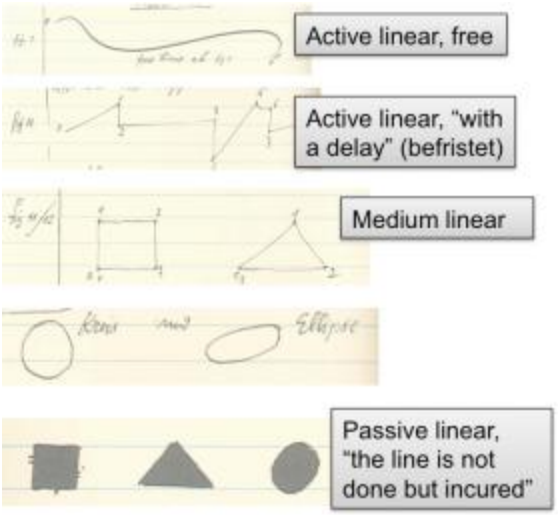


**Figure 9: A new language for lines (source: (Klee 2005))**

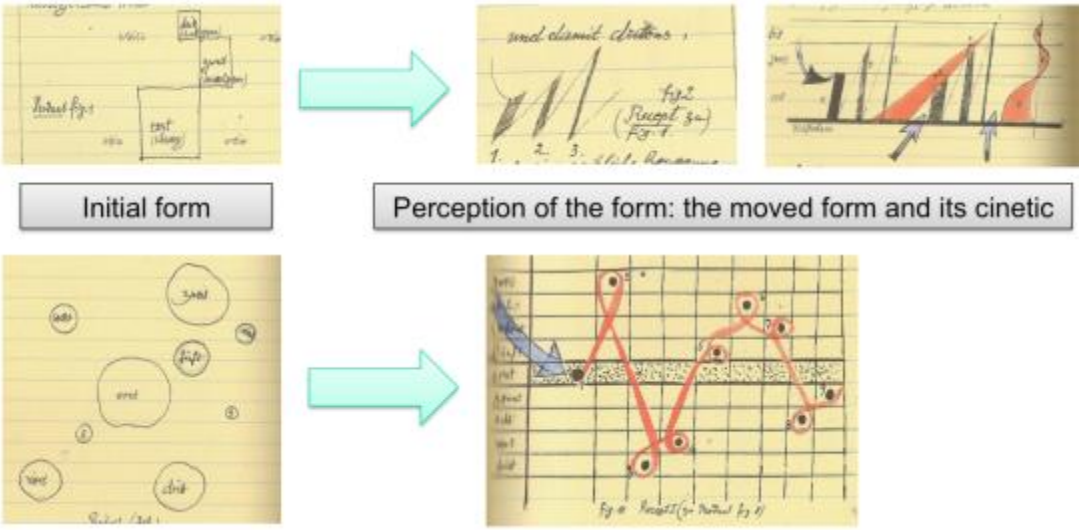


**Figure 10: A language of perception: pasturage and predation; the kinetics of the moved form (source: adapted from (Klee 2005))**

2- Each chapter of Klee's teaching not only investigates one dimension of the work (as did Itten for lines, surfaces, colour, textures, and so on) but discusses how one 'part' relates to the 'whole'. For instance, the 'line' is related to the 'perspective' of the whole piece, the 'weight' of each element is related to the 'balance' of the whole piece, the 'elemental structural rhythms' of the piece are related to the 'individual' that integrates all these rhythms, the 'joints' between elements are related to the 'whole organism', and the 'moved forms' are related to the 'kinetic equilibrium' of the received piece. This *part–whole* logic leads to a renewed logic of *composition*. In several exercises, Klee teaches composition. See the figures 11-12 for examples. Note that the composition criteria are not 'external' or stable evaluation criteria. They are *enriched by the work*. See, for instance, the example of 'balance' (figure 12). Klee considers that the 'balance' is a composition criterion, represented by the vertical cross (i.e., a balance with a vertical column and a beam). The superimposition of imbalanced situations creates a balance but this balance is not the initial vertical one but a 'cross-like' balance. The composition criteria create dense subsets of constraints. They are 'dense' in the sense that each composition has a balance (and

can thus help characterize all possible objects). This balance is obtained through different forms of expression means (constraints).

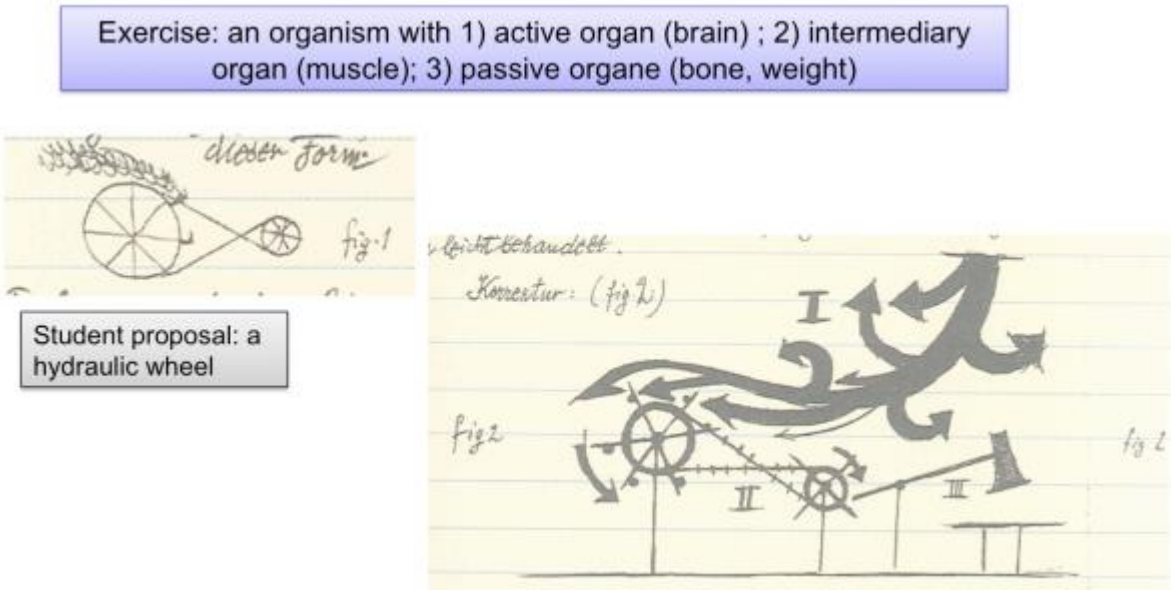


**Figure 11: Composition of a piece with three organs—discussion of a hydraulic wheel schema proposed by one student (left) (source: adapted from (Klee 2005))**

Klee supports the idea that a hydraulic wheel can be represented by these three organs and his drawing insists on the composition of these three organs (right). He explains changes to the drawing (right) in that the principal organ—the water—originally is drawn with an undulating structure that is a form of cliché, whereas its form should relate to its role as the main organ. He insists on 'the right choice in the relationship between the organs' ('active fall = brain; linked wheels = intermediary; hammer = passive organ'), 'the right choice in the form of the organs' ('main organ should appear in the most individual way and the others are gradually articulated downwards') and 'the right choice for emphasizing the relationship between the organs' ('main energy, intermediary energy, secondary energy').

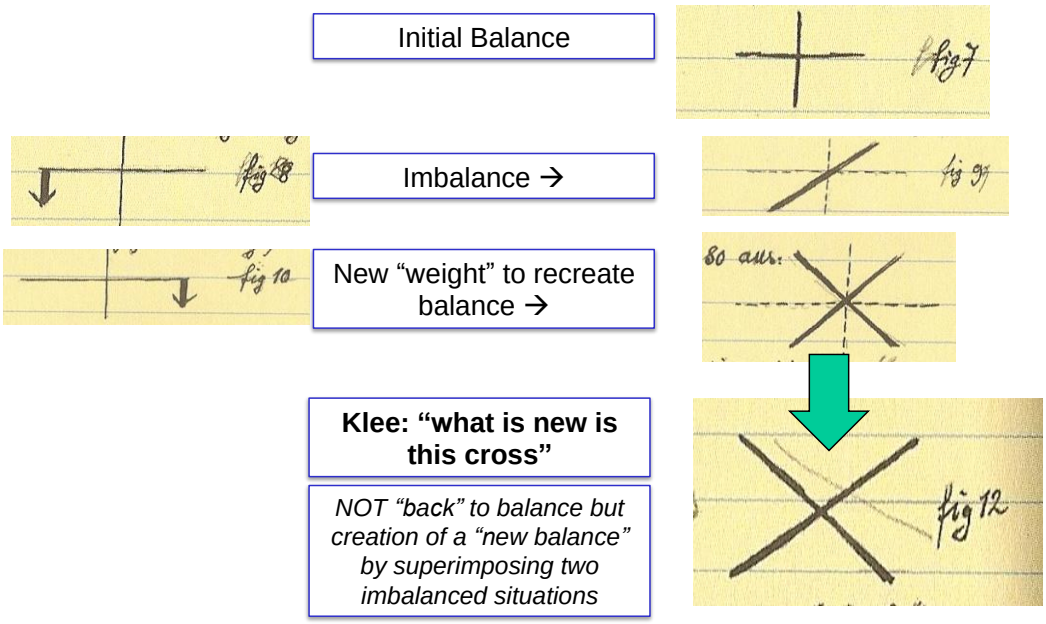


**Figure 12: Working on the 'balance' composition criteria (source: adapted from (Klee 2005))**

Initial situation: a 'balanced' composition, in which the balance is a scale that can be represented by a vertical cross ( horizontal line = horitzontal beam of the scale and vertical line = vertical rod of the scale). A new weight is then added to the composition (left), and the balance changes (right). To rebalance the composition, another

weight is added (left); i.e., a weight is *added* instead of the previously mentioned unbalancing weight being removed. A new 'balance' then emerges, which is no more like a scale but is like the superimposition of two imbalanced situations; hence there is another cross. As underlined by Klee, 'what is new is the cross, we don't go back to the initial balance but we create a new balance.'

3- Klee also teaches how *to shift from one aspect to another*. One example is given in his second chapter. Teaching the 'weight' and balance of a piece, Klee shows that the imbalance of surfaces (see figure 13) calls for a new 'weight' to be balanced (e.g., the imbalance of surfaces is balanced by a colour). However, the introduction of coloured surfaces leads to a new imbalance. The scale thus 'oscillates' and creates rhythms in the whole. This is a shift from weight and balance to scales and rhythm, which creates the 'spine' of the piece (see figure 13). This transition is mediated through music, in which 'weights' and 'balances' correspond to rhythms, tempi and bars.
The Klee teaching structure corresponds to the presentation of transitions: from perspective to weight (via gravity), from balance to rhythm (via scales, space and music), from individual to joints (via physiology), from joined individuals to organisms and organs, and from organism to 'moved form' (from the eye's perception). Formally speaking, this corresponds to the passage from one dense subset to another, and is hence a form of 'countability'.

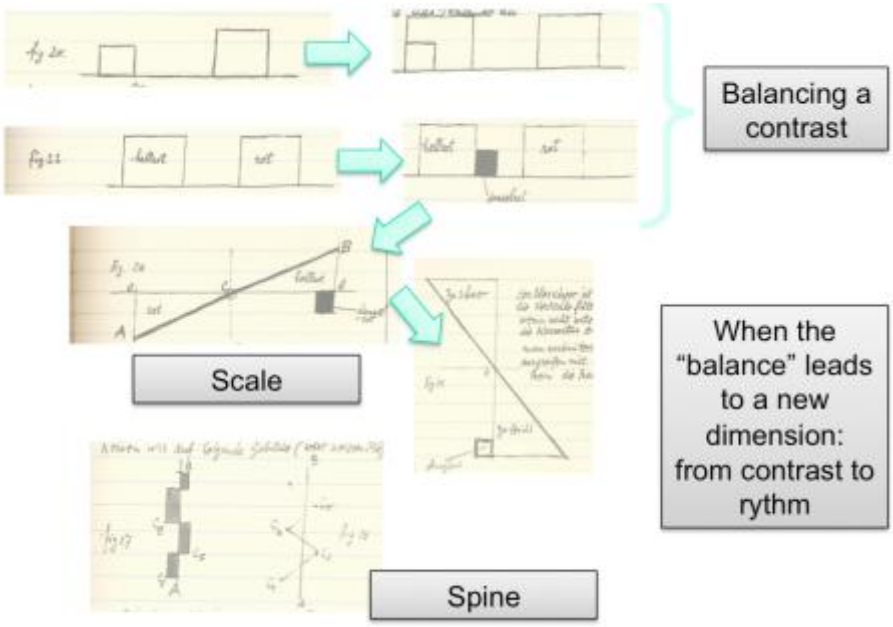


**Figure 13: Shifting from one aspect to the following one—the case of balance and rhythms (source: adapted from (Klee 2005))**

**Analysis of the Klee course from a design perspective**

How does Klee improve the design capabilities of the students? Let's first confirm that Klee's teaching can be related to teaching style creation.

To begin, let's underline that, just like Itten, Klee does not teach radically new expression means. The expression means discussed in Klee's teaching are reduced to drawing and painting (and do not even address texture, material or shape). Building on this reduced set of means, Klee rather teaches how to enrich them in that he provides students with a new language for lines, forms, motives, and 'joints'. Does Klee teach a pre-existing style? Just like Itten, Klee does not follow the usual categories of applied art teaching or

beaux art teaching (e.g., landscape, mythological scenes, and still life). He introduces a new language with which to speak of the composition and style of a piece of art: balance, rhythm, 'organic discussion', and 'kinetic equilibrium'. This language helps the artistraise questions about how to organize an 'organic discussion' between a line and a circle, how to build an organism that combines given organs (see the waterwheel exercise above), and how to provoke a predefined 'kinetic equilibrium' (i.e., not the work 'as such' but the work as seen by the viewer ('moved forms')); i.e., how to integrate this 'moved form' into the composition of the fixed form. In all these exercises (and particularly the last example), the notion of style creation is at the heart of the teaching.

We thus confirm that Klee's courses deal with a form of generic generativity. Let's now analyse the kind of design capabilities taught by Klee to improve generic generativity. To this end, we conduct an in-depth analysis of the design reasoning in Klee's exercises. We illustrate this analysis for one case, taken from the lesson on joints and composition of an individual with structural motives.

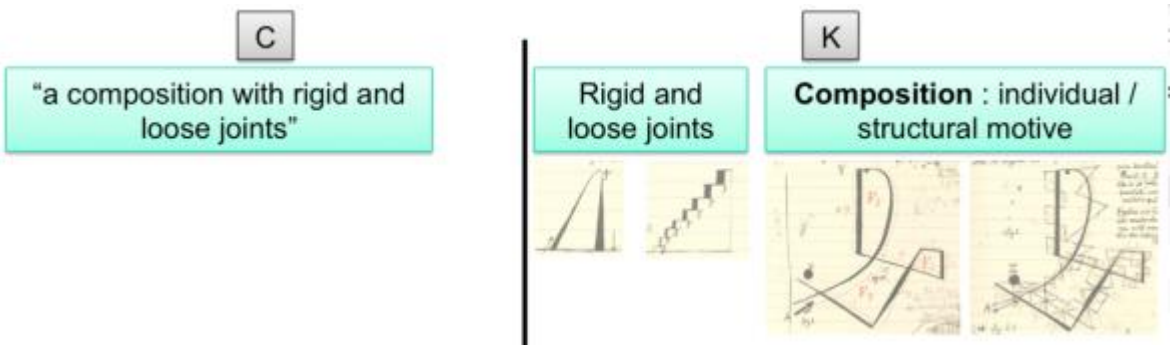


**Figure 14: C-K analysis of one Klee exercise ('joints and the individual')—initial state**

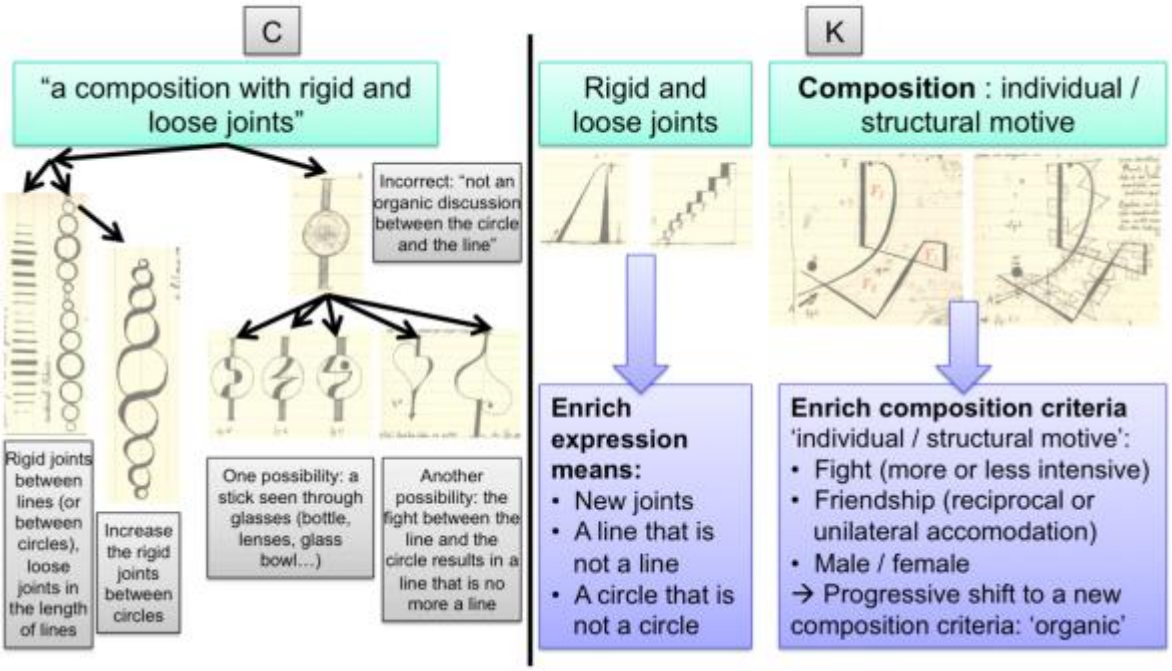


**Figure 15: C-K analysis of one Klee exercise ('joints and individual')—final state (pictures from (Klee 2005))**

For the initial state (figure 14), K contains the knowledge acquired during the lesson on joints and motives, while C contains the brief given at the end of the lesson as homework. For the final state (figure 15), in the following course, Klee goes through the students proposals with them. His remarks are coded in C or K expansions.

This case reveals the following aspects of Klee teaching.

1- The exercise is limited to *one type of composition issue (hence one dense subset) with one type of expression means (the constraints of the dense subset)*. Using 'joints', the artist is supposed to realize a composition via a discussion between the individual and a structural motive. Initially, the apprentice designer knows about two types of joints (rigid or loose) and about the composition of an individual based on structural motives (the previous lesson in the Klee course). The student explores how to create an 'individual' using rigid and loose joints. In his course, Klee discusses two alternatives, represented in C-space in figure 15: on the left side (in C-space, extreme far left solution), there are rigid joints between lines; on the right side (in C-space), there is an individual based on the 'discussion' between a line and a circle. The first answer ('rigid joints between lines') is said to be correct. Klee explains that there are rigid and loose joints and the articulation of rigid joints (between lines) and loose joints (in the variation of the lengths of the lines) creates an 'individual'. He proposes a variation—based on circles, where there are rigid joints between circles and loose joints in terms of the variation of circle diameters—and a variation of the variation—where with a bolder line Klee underlines the rigid joint between the circle and the loose joint and improves the composition. Hence, even with these very limited means, it is possible to create a rigorous composition of one individual based on structural motives.

2- The exercise leads to *an expansion of knowledge on expression means and composition criteria*. Working on the 'incorrect answer', Klee explains that 'there is no discussion between the line and the circle'; i.e. the play on joints does not create an individual with structural motives. Still, Klee shows that it is possible to evolve the drawing to get a correct answer. In so doing, Klee expands the expression means in that rigid and loose joints result from 'a stick seen through glasses like bottle lenses or glass bowls' or they result from the 'fight between the line and the circle', which leads to 'a line that is no more a line' and 'a circle that is no more a circle'. These 'lines', 'circles', 'stick and glasses' are new expression means for rigid and loose joints. Meanwhile, the composition criteria are enriched in that the relationship individual unity/structural motive is now 'a more or less intensive fight', or a 'friendship or reciprocal or unilateral relationship'. The individual can be a battle, or a friendship, with various criteria (e.g., intensive and reciprocal criteria). Hence, the exercise leads to the *enrichment* of the expression means and the composition criteria. However, this is not a form of 'densification' because the type of expression means is the same (joint) and the type of composition dimension is also the same (individual vs structural motives). Nevertheless, knowledge of these two types is denser.

3- The exercise creates a *shift to another dimension in composition*. The 'fight between the line and the circle' is not only a structural motive that creates an individual but also a male/female relationship that creates an 'organic discussion'. This notion of 'organic' is a new type of composition criterion in that it is not on the level of 'individual unity/structural motives' but on the level of the 'organic body/organs'.

These three aspects are more or less present in all of Klee's exercises and contribute to the important issue of Klee's courses: teaching a design *process* that helps the student to be generically creative. Let's underline these three features.

1- First, Klee focuses always on the genesis of the whole, in a constantly refined part—whole relationship. *Even ifeach step of teaching seems to address only one partial aspect of the final piece (e.g., perspective or balance), each of these aspects has to be consistent in itself at the level of the piece taken as a whole.In each step, Klee's teaching tends to validate a consistent part–whole relationship.* Klee's lessons show that certain types of elements (e.g., lines, 'weights', rhythm, joints, and organs) are in deep correspondence with one aspect of the final piece (e.g., the perspective, balance, individual, and organism). Each lesson consists of working on the relationship between one type of language (e.g., the language of lines or, 'weight') and the aspect of the whole related to that language (e.g., the perspective or balance). This is the generalization of the exercises where Itten proposed to work on a whole montage only based on textures. Klee always teaches the whole, even if it is the whole related to its parts. In each step, Klee teaches the whole piece as expressed by one type of language (i.e., the work is seen as a perspective/lines; the work is seen as a balance/'weights'; or the work is seen as an organism/the organs and joints). One can consider this as a logic of robustness. By working in each step on the part–whole relationship, Klee ensures that each of the languages (e.g., the language of perspective or balance) expressed by specific means (e.g., lines or 'weights') is 'present' in the final piece. The languages are applicable to all known pieces and form a frame of references. Additionally, Klee ensures that the new piece that emerges can be understood in all these languages, in this frame of reference. Formally speaking, each type of language (in one step) appears as a dense subset, and this type of language (e.g., the language of perspective or balance) applies to all known pieces and each type of language corresponds to certain types of constraints (e.g., lines or weights).

2- The part–whole relationship is *not* a one-to-one relationship. Instead, *work on the part–whole relationship expands the language of parts* (involving new types of joints, line circles, and so on) and *the language of the whole* (involving new forms for the relationship between the individual unity and structural motives). Hence, *each step of the process is also a step of creative expansion.* Formally speaking, it means that Klee does not teach dense subsets as such but teaches the capacity to create dense subsets.

3- Klee proposes a logic of *transitions* between the process steps. Let's analyse some of these transitions. The first language is the language of lines (part) and perspective (whole). Klee suggests that these lines and perspective define horizontal and vertical and relate those to the physical notion of gravity. Having introduced that notion of gravity, lines and perspective lead to a second language, based on weights (parts) and balance (whole). In this new language, the emerging object inherits the dimensions designed with line to build perspective (i.e., hopefully original ways to treat lines and perspective) and the heritage will be expanded in the new language (where the original lines and perspective will give birth to original treatments of weights and balance). Klee then shifts from this language of weights and balance to the language of structural rhythms and the paced individual by showing that a series of weights and imbalances and balances creates forms of music. After physics and music, the third transition is based on physiology (where the rhythms and the paced individuals are animated by joints that build an organism). These transitions appear arbitrary and they are certainly. However,

they ensure that the designer can shift from one language to the following one so that the genesis process leads to the *accumulation of a growing number of languages on the object*. *These transitions contribute to increase the genericity of the final piece.* Certainly, a master designer would not need such codified transitions and could invent his or her own. However, the designer should not neglect to invent such transitions, otherwise the genesis of his or her pieces would be limited to a (too) small number of languages, hence losing genericity. Formally speaking, this logic of transition from one language to another corresponds to a logic of countability of dense subsets. Klee teaches how to organize and walk the sequence of dense subsets.

Finally, these three features show that *Klee teaches a design process where each step makes a clear contribution to the final result (feature 1), where each step can be expansive (feature 2) and the steps are linked together to form a linear evolution (feature 3).* Klee teaches a process that ensures that the apprentice designer can accumulate many general languages for his or her piece, hence improving the genericity. This accumulation is based on two principles. The first is a constant concern with the 'whole', caught by dense subsets. Even if each step of the genesis addresses 'parts', each step also addresses an aspect that is valid at the level of the whole (e.g., perspective or balance). Hence, each steps leads to the 'validation' of one dimension of the 'whole' piece. The second principle is a process of accumulation that is based on neither deterministic laws nor independence principles (as in the case of systematic design) but is based on *transitions* between languages that keep the possibility of originality at each level (i.e., multiple paths open) and propagate the originality won at one level to the following level (i.e., there is no modularity). These transitions ensure that the genesis will accumulate as many contrasting (and still coherent) languages on the emerging piece, while keeping and increasing the generativity. This explains why this process is a *generic creative design process*.

**Formally speaking, H2 and H3 are confirmed for Klee's teaching: generic generativity can rely on countable dense subsets.**

**Comment on Klee's teaching: similarities and differences with engineering design approaches**

Returning to engineering design, we can only be struck by the fact that the languages of the engineering design process can precisely appear as *languages of the part–whole relationship*. For instance, systematic design (Pahl et al. 2007) relies on four well-identified languages: functional, conceptual, embodiment, detailed. Validating a list of requirements finally consists of checking the consistency of the emerging object on the functional dimensions. The parts are functions, while the whole is the functionality of the final object. The part–whole relationship is acceptable when the list of functions corresponds to a functional object. The same holds at the conceptual level (where the consistent combination of technical principals is supposed to address the conceptual design of the product), at the embodiment design level (where the consistent arrangement of organs is supposed to build a coherent organism) and at the detailed design level (where the fine adaptation of industrial components builds an industrially feasible product).

Still, there is one major difference between the two processes. In the logic of systematic design, designers work with a knowledge base that is structured by determinism (i.e., engineering science laws) and independences (i.e., modules). In this case, the

interactions between the levels are simplified and purely driven by the deterministic laws (because the relationship between the languages is either a pure determinism or an independence in that either a function determines a technical principle or, by constrast, whatever the function, one technical principle can be used, namely modularity). If the knowledge base is non-deterministic and non-independent, then the transition from one language to another is no longer defined by the deterministic rules. Additionally, Klee, just like Itten, builds a knowledge base that is non-deterministic and non-independent. We find that Klee makes the same effort to always propose multiple paths (i.e., there are no deterministic rules and not one solution to an exercise given by Klee) and to always show that the attributes and the effects created at any moment in the genesis affect the rest of the design process. If there are no deterministic rules with which to structure the design process, then how is it possible to shift from one type of language to the next language, and what is the order of the process steps? The magic of Klee might lie precisely here: the invention of a logic of transitions, based on a specific language (e.g., the language of physics, music, or physiology) that might appear far from the genesis of the object but provide at least one possible order to approach many different facets of a composition.

## Part 5: Conclusion—discussion and further research

We can now conclude our work and answer our research questions.

1- The courses of Itten and Klee not only aimed at teaching the past style and a new style. They also aimed at increasing students creative design capabilities and even, more precisely, at providing them techniques with which to create their own style, in the sense of being able to be generically creative. We thus confirm H1: creative design corresponds to generic generativity.
2- The analyses of the two courses identify two features critical to having a generic creative design capability.
    a. A knowledge structure that is characterized by non-determinism and non-independence. Hence, we confirm H2: a splitting knowledge base is required for generic generativity.
    b. A genesis process that helps to progressively 'accumulate' languages on the object in a robust way. This accumulation is based on step-by-step work on part–whole relationships and a series of transitions from one language to another one. Hence, we confirm H3: the countability of dense subsets can define a design process.

We thus confirm for Bauhaus courses the propositions that were predicted by theory. This is all the more interesting in that the propositions were not necessarily self-evident. At a time where one tends to assume that creative design is related to ideation and the birth of original ideas, design theory predicted that the knowledge structure plays an important role in generativity.

This work has an impact on several domains.

1—*Regarding Bauhaus*, this analysis, based on advances in design theory that today provide a unified analytical framework, helps underline that Bauhaus was neither a school

that taught a particular style nor a school that taught design techniques but fundamentally *a school that taught how to systematically invent new styles*.

From the perspective of style creation, we can *discuss the role of technique and taste (i.e., new social trends)* and their place in teaching. Surprisingly, neither Itten's nor Klee's teaching places strong emphasis on new techniques or new tastes. They more deeply focus on the reasoning logic that helps to create new style without even relying on new techniques or new 'tastes' or social trends. It was as if they were trying to teach in the 'worst case' situation. The rest of the Bauhaus program taught students how to deal with new techniques or new social trends. Based on the introductory courses, it was certainly easier to think of style creation in terms of a 'techno-push'; i.e., relying on a newly invented technique (see the work on texture, which students could freely extend to photography or today to new digital imaging) or in terms of 'market-pull' (i.e., relying on new composition dimensions as would do an artist working today on 'sustainability' or 'transparency').

More generally, this work provides a deeper understanding of the relationship between art and technique in design. The use of 'texture' or more generally 'expression means' is just a technique. However, they are not necessarily splitting or non-splitting. The art of designers is not limited to making use of a technique to design an object. More generally, design consists of mobilizing a technique to build a knowledge base that is splitting or not.

2—This work provides results for *engineering design*. The comparison helps show that systematic design is precisely characterized by knowledge structures that *prevent the splitting condition* and that are characterized by independence (modularity) and determinism (engineering science). This clarifies one critical aspect of systematic design, namely avoiding 'going out of the box'; i.e., avoiding generic generativity. Modular and deterministic generativity might be encouraged, as long as they create a knowledge base that remains non-splitting.

From this perspective, we can wonder whether compatibility with the splitting condition could characterize professions. We should insist here that the logic of designing with (respectively without) the splitting condition is not intrinsically the logic of engineering design (respectively industrial design). Engineering design can also be driven by a logic of innovative design. Several works have long underlined a logic of breakthrough and unknown exploration in engineering design (Kroll 2013 ; Kroll, Le Masson et Weil 2014 ; Shai et al. 2013 ; Taura et Nagai 2012). This is deeply coherent with the results of this paper: *in innovative design, engineers reverse the logic, they use engineering science and engineering techniques to build a knowledge base that follows the splitting condition* (see in particular the analysis of breakthrough projects in military weapons published by (Lenfle, Le Masson et Weil 2014, 2015)).

Conversely, generic generativity might not necessarily be the logic of industrial design. In some cases, industrial design might favour the elaboration of knowledge bases that are non-splitting. An interesting illustration of this situation is the very early integration of 'industrial designers' in industrial processes by Wedgewood, the famous earthenware inventor, in the late 18$^{th}$ century (Forty 1986), where designers were actually in charge of inventing the forms of plates that would support several, varied ornaments. Today the talent of designers might precisely be to create knowledge bases that are locally splitting and non-splitting.

3—This work contributes to the debate on the relationship between engineering design and industrial design and their respective roles in the design processes. It underlines that the critical activity is not only the creation of a new artefact but it is also the moment where designers 'prepare' their knowledge base, to 'split' it (or to 'unsplit' it). Both actions (splitting

and unsplitting) are important. It might be that industrial design could help engineers split their knowledge base, if necessary, to open paths to innovative design. Conversely, engineers might help industrial designers to 'unsplit' their knowledge base to facilitate rule-based design (see, (Brun, Le Masson et Weil 2015)).

4—Finally, this work contributes to design theory. We began the paper with a condition on generativity. This appears as a 'negative' result of the theory, whereas we tend to think that the only limit to generativity is fixation and imagination capacity, design theory predicts that there is also a condition on the structure of knowledge used in the design process—the knowledge base has to meet the splitting condition. The work on Bauhaus leads to the positive interpretation of this condition in that it shows that teachers in the field of design are actually able to help students build a knowledge base that meets the splitting condition. Teaching design (for generic generativity) finally consists of enabling the splitting condition. Hence, our study on Bauhaus teaching also raises a question on design education: does design education today (be it engineering design education or industrial design education) teach 'splitting knowledge' or, even more, does it provide students the capacity to themselves acquire and create new knowledge to meet the splitting condition?

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# Day 2: Room V111-112-113 / V114 / V115 / V116 / V119

| Day 2 - 28 Jan 2021 | | | |
|---|---|---|---|
| **Timetable** | **Type of Course** | **Title Course** | **Speakers** |
| 9:00 - 10:00 | **Breakout groups (2/5)** | Exploring your thesis with Design Theory | Professorial College |
| 10:00 - 11:00 | **Basic course:** Contemporary Formal Models II | Enhanced parameter analysis method | Ehud Kroll |
| 11:00 - 11:30 | **Break** | | |
| 11:30 - 12:30 | **Breakout groups (3/5)** | Exploring your thesis with Design Theory | Professorial College |
| 12:30 - 14:00 | **Lunch** | | |
| 14:00 – 15:00 | **Basic course:** Contemporary Formal Models III | Knowledge structure in design (n-dim, category theory, matroïd, sp splitting condition) | Eswaran Subrahmanian |
| 15:00 – 16:00 | **Advanced topic / Paper discussion (3)** | Biomimetics with design theory (Vendôme classroom, visioconf) | Jacquelyn K.S. Nagel |
| 16:00 - 16:30 | **Break** | | |
| 16:30 - 17:30 | **Advanced topic / Paper discussion (4)** | Axiomatic Design for Creativity, Sustainability, and Industry 4.0 | Christopher Brown |
| 17:30 – 19:30 | **Cocktail** | | |

## Ehud KROLL

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**Title of the Presentation:**

Enhancing the parameter analysis method with design theory

**Synopsis:**

The empirically-derived parameter analysis method presents an approach to conceptual design that is very different from systematic design's. Parameter analysis has been studied with the help of C-K Theory to uncover and explain its underlying logic and efficiency. It was found to resemble a sort of branch-and-bound algorithm that operates on the "unknown" and also involves learning while designing.

**Main References/ Further readings:**

Kroll, E., Condoor, S. and Jansson, D.G. (2001) *Innovative Conceptual Design: Theory and Application of Parameter Analysis,* Cambridge University Press.

Kroll, E. (2013) Design Theory and Conceptual Design: Contrasting Functional Decomposition and Morphology with Parameter Analysis, *Research in Engineering Design*, Vol. 24, No. 2, pp. 165-183 (special issue on design theory).

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DOI 10.1007/s00163-012-0149-6

ORIGINAL PAPER

# Design theory and conceptual design: contrasting functional decomposition and morphology with parameter analysis

**Ehud Kroll**

Received: 27 February 2011 / Revised: 21 June 2012 / Accepted: 11 October 2012 / Published online: 26 October 2012


**Abstract** Over the last several decades, functional decomposition and morphology has become the most common conceptual design method to appear in design textbooks. Although criticism toward systematic design in general and functional decomposition and morphology in particular has increased, most design educators keep teaching this method. Some of its weaknesses are demonstrated in this paper on a textbook example, followed by proposing parameter analysis as an alternative or complementing methodology. Parameter analysis was initially developed as a descriptive model of reasoning in design and later turned into a prescriptive model for doing innovative conceptual design. This methodology centers on repeatedly identifying dominant conceptual-level issues and relationships ("parameters"), implementing these concepts as configurations, and continuously evaluating the evolving design. The usefulness and power of parameter analysis are shown through several case studies, its relation to modern design theories, and its applicability to training designers. The tight connection between the teaching and practice of engineering design suggests that adopting a new educational methodology will bear fruits in industry a short time thereafter.

**Keywords** Conceptual design · Functional decomposition · Morphology · Parameter analysis · C–K theory

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## 1 Introduction

Two kinds of engineering design process models exist: descriptive and prescriptive (Finger and Dixon 1989). A third category, of computer-based models, has also been studied but we shall ignore it here. Descriptive models aim to understand *how designers design*, that is, what processes, strategies, and methods they use. Prescriptive models, on the other hand, prescribe *how the design process ought to proceed*. There is also the type of prescriptive models that address the design artifact and its attributes, not the design process, but these are less relevant to the current paper. Examples of the last category are Suh's axiomatic design (Suh 1990, 2001) and the Taguchi method (Taguchi et al. 2004). The former encourages designs that maintain independence of the functional requirements and minimize information content. The latter promotes reducing the effects of variation in manufacturing and the environment on performance by properly setting the values of some of the design variables. Moreover, it is sometimes unclear whether a model is descriptive or prescriptive, since the intention behind most descriptive models is that they should eventually be used as a prescription for doing design. In general, it seems that there are many more descriptive studies, attempting to deepen our understanding of existing design processes, than prescriptive investigations that propose specific methods and steps to accomplish a good design process.

Most existing prescriptive models are based on German work on "systematic design," or the "rational model," from the 1970s[1] (Hubka 1980; Hubka and Eder 1996;

[1] The origins of systematic design can actually be traced back to the industrial revolution in the mid-nineteenth Century, as reported in (Wallace and Blessing 2000) and Section 1.2.2 in Pahl et al. (2007).

Pahl et al. 2007), with many British (Pugh 1991; French 1999; Cross 2008) and American (Otto and Wood 2000; Ulrich and Eppinger 2007; Ullman 2009) adaptations in engineering design textbooks. The models prescribe a sequence of major stages for the design process (clarifying the task, drawing the specifications, conceptual design, embodiment design, etc.) and offer various tools for each stage. The emphasis in Pugh (1991) is on a "controlled-convergence" process with the aid of a decision matrix (Pugh's method is commonly used for concept selection, but his original writing refers to a complete design method). Most researchers and practitioners roughly agree on those prescriptive models, which were also adopted in software engineering as the "waterfall" or linear sequential model (Pressman 2001) and in systems engineering as the stage-gate model (Cooper 1990).

Of particular relevance here is what systematic design offers as the method for conceptual design: functional decomposition and morphology. Under this scheme, the main function of the artifact is decomposed into finer and finer subfunctions, solution principles or "subconcepts" are sought for each subfunction, and finally, the subconcepts are combinatorially assembled to form multiple overall design concepts. This method is very popular in university design courses due to its structured character and ease of use. However, over the last few years, there has been considerable criticism of this design process model. According to Brooks (2003), "…the rational model of the design process…such as Pahl & Beitz… is dead wrong and seriously misleading." He further argues that this design model is not followed by expert designers, does not capture the dynamics of the design process, and results in "bizarre"[2] results (Brooks 2007). Later, Brooks devotes a whole chapter of his book to elaborate the weaknesses of the rational model of design, quoting many prominent design researchers (Brooks 2010, chapter 3).

While this criticism is directed more toward the overall nature of the rational model as a problem-solving paradigm, similar notions have been expressed in regard to the conceptual design aspect, including the implicit assumptions that a solution-neutral function structure can be developed without thinking of solutions, that all the subfunctions are independent and discrete, and that each concept in the working structure satisfies one and only one subfunction (Chakrabarti and Bligh 2001). An empirical study concluded that the excessive functional decomposition led to a lack of freedom for the designer and adversely affected innovation and creative performance (Leenders et al. 2007). Kroll and Condoor (2009) also investigated some of the problems associated with the systematic design model and showed that most of them stem from the linear or sequential nature of the process. Le Masson et al. (2010) distinguish between two types of design: "rule-based design," which includes systematic design, and "innovative design." The former is applicable to circumstances where the knowledge ("rules") is well-established and relatively structured, and the designer attempts to use it whenever possible. The latter is more relevant to new situations, in which the knowledge may not exist, may need to be discovered and explored, and the resulting design artifact may assume a new and surprising identity.

The stage of the design process referred to as "conceptual design" is usually regarded as the transition from a need that has been stated and analyzed to form the design specifications or requirements list, to a solution concept. However, how detailed this solution concept should be remains unclear. Sometimes, it consists of just a few sentences describing the main ideas or working principles to be implemented, while in other contexts, it may include a fairly elaborate graphical layout of the structure of the solution. The differences may stem from the type of design task being addressed, whether it is a relatively routine one or a totally new situation, or from company-specific administrative considerations. Clearly, the design process should eventually end in a completely specified configuration, and the activities required to reach it will take place anyway, so where exactly the line between conceptual design and subsequent stages is drawn may not be that important. What matters more is that the early design activities are the most significant in terms of their influence on the final outcome and therefore should be constantly studied and improved.

From the design theory perspective, the role of conceptual design can be described as the reasoning stage that accepts as input the description of the problem to be solved (the solution being the unknown) and produces as output a description of solution(s) that attempts to minimize the unknown, so subsequent stages (embodiment and detail design, prototyping, testing, etc.) will be mostly technical in nature and will use existing and available knowledge. The design-theoretic question regarding conceptual design now becomes: what reasoning process or strategy will take us from the input to the output (i.e., will add known things to the unknown) in a way that will produce more robust and innovative artifacts, especially in new situations, when not all the knowledge is available at the beginning and when the solution may lie outside the boundaries of the current problem domain.

The paper will demonstrate some of the weaknesses of the functional decomposition and morphology method of conceptual design on a textbook example of designing naturally-driven bilge pumps. Next, another methodology, called *parameter analysis,* will be introduced and applied

[2] A good example of "bizarre" results is the nail clipper in Ulrich and Seering (1990), where separate structural elements are used to satisfy each subfunction, resulting in a 'Rube Goldberg design'.

to the same example, followed by a case study of designing aerodynamic decelerators for small sensors that will be used to show the creative power of parameter analysis. The use of parameter analysis to capture design rationale and its relation to the modern C–K Theory of design will also be examined, with a discussion of how to use the methodology for training designers. Contrasting two design methods may be done by different ways and criteria (Reich et al. 2012). In this paper, we chose a combination of describing and demonstrating *what* each method does, and theory-based analysis to attempt to explain *why* the methods differ. The informal criteria used for the comparison include the area of relevance (i.e., the type of situation in which the method can be applied), efficiency of the reasoning process, and ability of the method to produce innovative and robust results. Being based on case studies, the evidence and validation provided in this paper are clearly limited. Our intention is to highlight the differences between the two design methodologies, suggest explanations for them, and let the readers draw their own conclusions.

While parameter analysis as a methodology for innovative conceptual design has been introduced in Kroll et al. (2001), the current paper makes some important contributions. First, it contrasts parameter analysis with functional decomposition and morphology. Second, it looks at parameter analysis from the design theory perspective and attempts to provide empirical validation of C–K Theory. Third, it relates the parameter analysis methodology to the important need of capturing the rationale of the conceptual design process.

Before proceeding, a word about the term "parameter analysis" is in order. Unfortunately, "parameter" in engineering can mean almost anything; thus, the term "parameter analysis" does not imply even remotely that it refers to a design methodology. To the best of our knowledge, the term first appeared in Li et al. (1980) as a broad methodology for training innovators. It has since been developed by the author and his colleagues into a prescriptive model of carrying out conceptual design (Kroll et al. 2001); however, in recognition of the original work, we chose to retain the name of the methodology for now. In the future, if and when it undergoes major revisions, a name change will be considered.

## 2 A critical look at functional decomposition and morphology

The following example is taken from a design textbook (Otto and Wood 2000) and is typical of many similar examples. We do not intend to criticize the quality of this design, nor do we pretend to be familiar with all its aspects. The purpose is only to demonstrate some weaknesses of the functional decomposition and morphology method.

Figure 1 is the function structure developed for a device to remove water from the bilges of unattended boats by using natural energy sources. The design requirements included a minimum of 8 L/h of water removal capacity, size of less than 1 $m^3$, and cost of less than \$50. Next, the subfunctions of Fig. 1 were entered as the first column in a morphological chart, and solution principles for each subfunction were sought and entered too. A portion of this chart is shown in Fig. 2. Several combinations of overall product concepts are formed by selecting subconcepts in each row

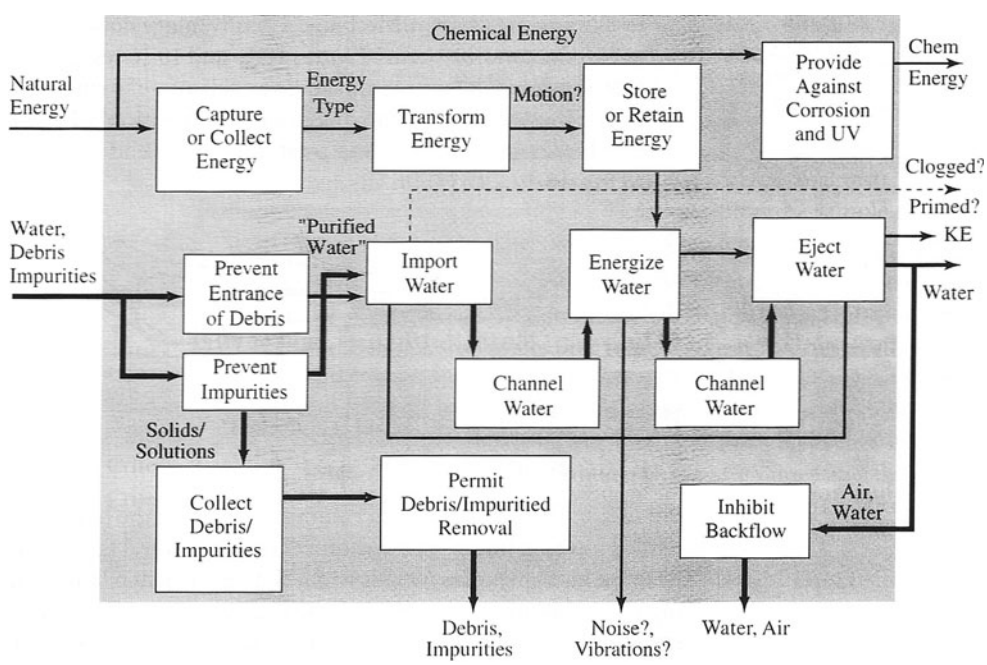



**Fig. 1** The function structure for the bilge pump (Otto and Wood 2000)

| Energy / Sub-function | Mechanical | Fluid |
|---|---|---|
| Capture Energy | **Linear spring,** Torsional spring, Pendulum, Elastic, Mass / spring. | Air: Propeller, Vanes, Cup Water: Hydraulic head, Turbine, Float |
| Transform Energy | Crank shaft, Gears, Belt / sprocket, Four bar, Cam, Rack & Pinion | Pneumatic / Hydraulic |
| Import Water | Lift, Wheel (rotary) Archimedes screw, Carousel, | **Suction,** Siphon, |
| Channel | Conveyor, Lift, Archimedes screw | **Tube,** Funnel, Jet, V-notch |
| Energize | **Reciprocating,** Screw or Rotary **pump** | Jet pump, Vaporize, Water column, |
| Channel | Conveyor, Lift, Archimedes screw | **Tube,** Funnel, Jet, V-notch |
| Eject | Lift, | **Pressure,** Jet |
| Inhibit Back flow | Flapper, **Ball,** or Butterfly **valve,** | |
| Prevent Debris / Impure. | **Screen,** Filter, Permeable membrane | Float, Skim, Vortex |

**Fig. 2** A portion of the morphological chart for the bilge pump (Otto and Wood 2000). Markings of one combination of subconcepts were added

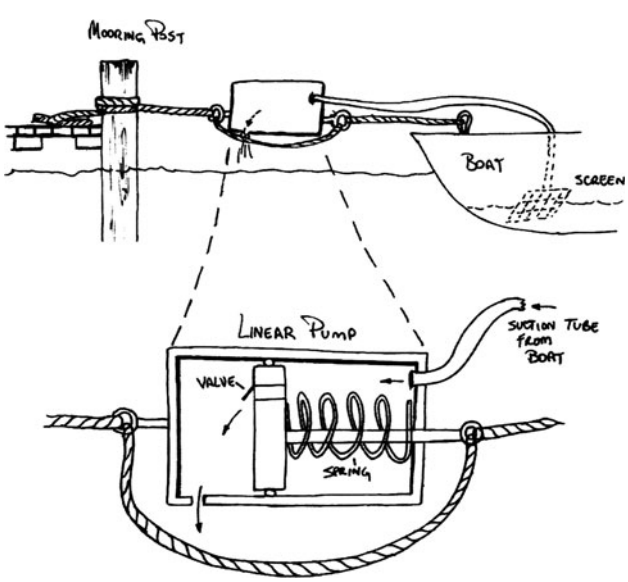



**Fig. 3** One concept for the bilge pump that uses wave energy (Otto and Wood 2000)

of the chart. One such combination consists of the marked items in Fig. 2, leading to the product concept of Fig. 3. It includes using the boat movement relative to a mooring post as the energy source, capturing this energy by storing it in a linear spring, which drives a reciprocating pump. The pump produces suction and pressure to move the water through a screen filter, tubes, and flapper valves. Other combinations led in the original example to several other concepts that were shown as sketches similar to the one in Fig. 3.

Let us examine this example in depth. We can see in Fig. 1 that the function structure is not at all trivial, but rather quite complex for a relatively simple design task. It includes five subfunctions (those with "water" as the noun) that together describe what engineers call "a pump". It also includes subfunctions that may not be essential, such as "transform energy," as becomes clear from examination of Figs. 2 and 3. On the other hand, it is unclear why the subfunction "permit debris/impurities removal" was generated and not "remove debris/impurities." It is also interesting to note that the function structure of Fig. 1 led, in the case of the design of Fig. 3, to actually designing a reciprocating pump from scratch, while another concept generated in the original example (Otto and Wood 2000) and not shown here used a rotary pump as an off-the-shelf item.

In general, functional decomposition seems to be a relatively difficult and time consuming task. Designers are often reluctant to make the required effort here instead of proceeding quickly to synthesizing a solution. The ability of designers to think in abstract terms and carry out a solution-independent functional decomposition is also questionable. Moreover, in real life, some functions can only be discovered in the context of a particular solution. Such functions cannot be identified during the initial functional decomposition activity but should be considered by the designer later in the process. In spite of many attempts to formalize the functional decomposition process (for example, Erden et al. 2008), it seems that different designers will almost always come up with different results; something that is completely reasonable in design in general, but surprising when it comes to a rigorous analysis method that is independent of any particular solution.

Figure 2 raises other issues. The chart contains a wealth of information, which might be difficult to process simultaneously in the designer's mind. All the subfunctions are listed as equal entities, so the designer needs to think about major issues, such as how to capture the natural energy (e.g., boat motion on the waves) and what type of pump to use, together with marginal concerns, such as moving the water from one location to another ("channel" subfunction) and filtering the water flowing into the pump. Moreover, some solution principles, or subconcepts, seem superficially forced: a pump is the obvious solution to this design problem, yet the chart lists subfunctions of the pumping action ("import water," "channel," "energize," "channel" again and "eject"). It may also lead to illogical combinations of subconcepts, such as using a pump to "energize" the water together with two Archimedes screws to "channel" the water. In fact, an Archimedes screw is a

pump by itself, so there might not be a need for the "energize" subfunction at all.

As with most textbook examples of conceptual design by functional decomposition and morphology, the concept generated in Fig. 3 lacks quantification at this stage but is nevertheless considered ready for a formal selection process. Admittedly, the original example (Otto and Wood 2000) has some analysis associated with it, but this was done later, under the title of "concept embodiment."

While this example is quite simple, we should also question the ability of a designer to generate a design such as shown in Fig. 3 "in a single pass." Suppose the designer generated the marked combination on the morphological chart of Fig. 2. Was the sketch of Fig. 3 a direct result of the verbal description of the subconcepts combination, or was there an iterative effort that culminated in Fig. 3? We believe the latter is the case, but nowhere in systematic design textbooks there is a formal process for developing the subconcepts combination into a concrete embodiment. Indeed, Pahl et al. (2007) say that concept variants must be firmed up—given concrete qualitative and rough quantitative definition—before they can be evaluated. However, there is no clear process for carrying out this development stage, except for mentioning that the methods should be similar to those used during conceptual design.

In summary, functional decomposition and morphology as a method for carrying out conceptual design exhibits the following weaknesses:

(a) Developing a solution-independent function structure is difficult and does not integrate well with the natural flow of activities during design,
(b) The breadth-first manner of treating subfunctions and their corresponding subconcepts may distract the designer's attention and prevent focusing on the dominant issues,
(c) The conceptual designs generated usually lack quantification and therefore have not been proven viable,
(d) There is no prescribed concept development process for transforming the collection of individual subconcepts into a coherent conceptual design.

## 3 Parameter analysis: development of the prescriptive design model

Work done at MIT in the 1970s resulted in a book (Li et al. 1980) outlining an approach to train innovators at universities and industry that employs several important ideas that formed the basis for parameter analysis. This has been further developed into a conceptual design methodology (Jansson 1990; Kroll et al. 2001). We begin by briefly describing the process of inventing a patented tiltmeter (Li 1976), first reported by Jansson (1990), and later in Kroll et al. (2001), because of its importance to the present discussion.

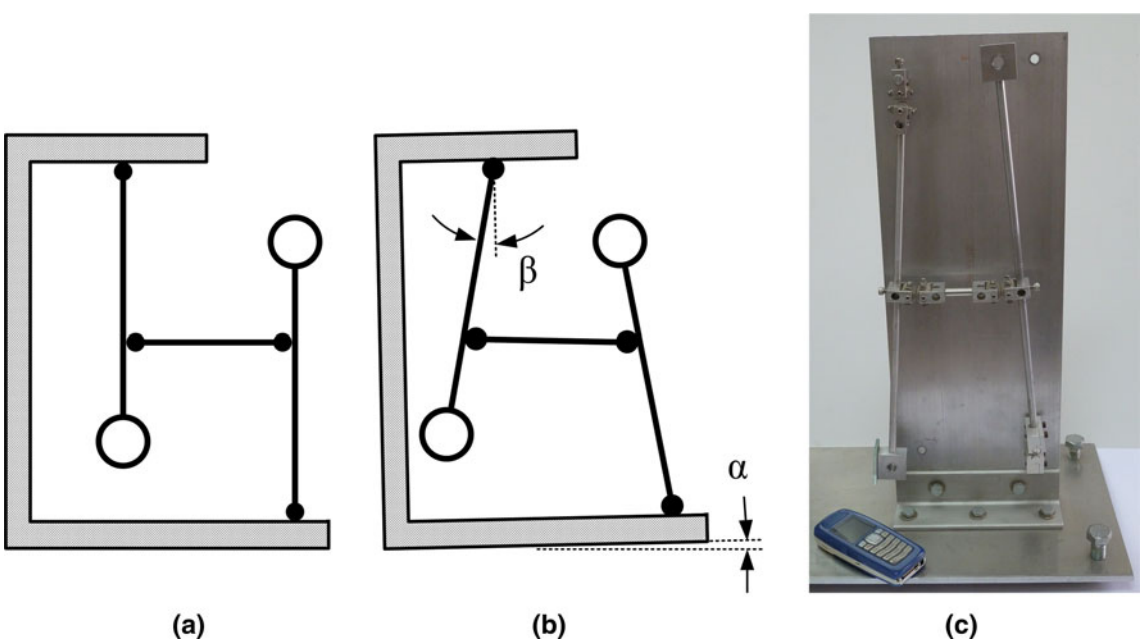



**Fig. 4** **a** The tiltmeter with no input angle, and **b** an input angle $\alpha$ produces a response $\beta$ where $\beta \gg \alpha$. The *large circles* are weights, *small solid circles* are hinges, and the *lines* represent stiff rods. **c** Photo of a working model of the tiltmeter

### 3.1 Development of the initial descriptive model

The mechanical device shown in Fig. 4 is a tiltmeter used to measure very small angles of tilt with respect to the local gravity vector. It consists of a regular pendulum coupled with an inverted one through a cross-bar and produces a large mechanical amplification.

The inventor knew that a simple pendulum could be used to measure tilt; however, a very long device, of the order of 50 m, would be required for the small angles that needed to be measured. He then realized that a simple pendulum being displaced laterally can be thought of as a spring, that is, obeying the relationship $f = k\ \Delta x$ ($f$ being the restoring force, $k$ the spring constant, and $\Delta x$ the displacement). Now, the statement that the pendulum needs to be very long is equivalent to requiring a very soft spring (small $k$). But how could a small $k$ be obtained when the physical dimensions should be kept small (of the order of 0.5 m)? Here the inventor had the idea of using the difference between two large spring constants (short pendulums) to yield a small $k$ (effectively long pendulum), that is, $f = (k_1 - k_2)\ \Delta x$. The last relationship requires a negative spring, that is, one that produces a force in the direction of the disturbance as opposed to a restoring force, and this can be provided by unstable devices such as an inverted pendulum. All that remained at this point was to couple the two pendulums at a point at which the resultant spring constant is small but positive, thus producing the desired high sensitivity.

The inventor knew that the last configuration would not work satisfactorily if friction were present in either the hinges or the yet-to-be-designed sensor for measuring the pendulums' tilt. He therefore included in the patent (Li 1976) a description of flexure-type hinges (realizing that full rotations were not necessary) and frictionless capacitor-type displacement sensor.

Observing the above thought process, it was concluded that conceptual design is carried out by movements between two spaces, *concept space* and *configuration space*. The former contains the ideas while the latter encompasses the representations of physical devices. Moving from concept space to configuration space represents a realization of an idea in a particular hardware, while the opposite is an abstraction or generalization from a specific configuration to a new idea. This descriptive model is shown in Fig. 5 with the tiltmeter design process depicted as a sequence of "moves."

Note that this model describes a sequence of events that represents a development process. It prohibits direct movement within configuration space and allows one configuration to evolve into another only through a "visit" to concept space.

### 3.2 From descriptive to prescriptive model

While the model of Fig. 5 attempts to explain what takes place during design, the practitioner will find it more useful to be presented with a prescriptive model that tells what to do in order to develop a concept. This has been accomplished by defining the steps that should be applied repeatedly as *parameter identification, creative synthesis* and *evaluation*. These steps are shown in the diagram of Fig. 6, where they are imposed on the descriptive model of movements between concept space and configuration space, as elaborated below.

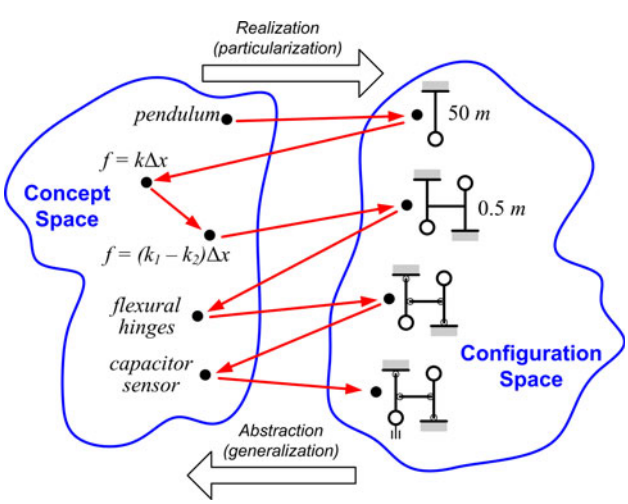



**Fig. 5** A descriptive model of the conceptual design process of the tiltmeter as movements between concept and configuration spaces

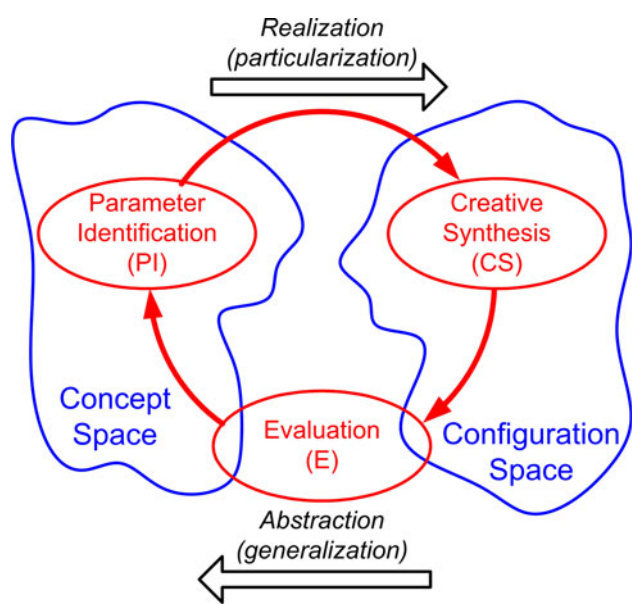



**Fig. 6** The prescriptive model of conceptual design consists of repeatedly applying parameter identification (PI), creative synthesis (CS), and evaluation (E)

#### 3.2.1 Parameter identification (PI): conceptual-level issues

This step consists of the recognition of the most important issues at any given moment during the design process. The "parameter" may include the dominant physics governing a problem, a new insight into critical relationships between some characteristics, an analogy that helps shed new light on the design task, or an idea indicating the next best focus of the designer's attention. Parameters play an important role in developing an understanding of the problem and pointing to potential solutions. The parameters within a problem are not fixed; rather, they evolve as the process moves forward. Some parameters identified in the tiltmeter example of the previous section were "measuring tilt with a simple pendulum," "looking at a pendulum as a spring," and "subtracting two large spring constants to produce a soft spring."

#### 3.2.2 Creative synthesis (CS): generation of configurations

This part of the process includes the generation of a representation of a physical configuration based on the concept recognized within the previous parameter identification step. The configuration synthesized here should be quantified to the extent that its behavior could be assessed, and this usually requires not more than rough, "back-of-the-envelope" calculations. The tiltmeter design, for example, mentioned a 50-m-long simple pendulum as the initial realization of the concept of a pendulum for measuring tilt and later, a double-pendulum configuration that was $\sim$0.5 m in length.

#### 3.2.3 Evaluation (E): constructive criticism

This step facilitates the process of moving away from a physical realization back to parameters or concepts. Evaluation is important because one must consider the degree to which a physical realization represents a possible solution to the entire problem. Evaluation also points to the weaknesses of the configurations. Evaluation should not usually resort to analysis of physical configurations that goes any deeper than is required to create a fundamental understanding of its underlying elements. Evaluation in parameter analysis is not a filtering mechanism. The main purpose is not to find fault but, rather, to generate constructive criticism. A well-balanced observation of the design's good and bad aspects is crucial for pointing up possible areas of improvement for the next design cycle.

### 3.3 The dynamics of the design process

Parameter analysis shifts the burden of truly creative activity from creative synthesis, the implementation of an idea in hardware, to parameter identification, the creation of new conceptual relationships or simplified problem statements, which lead to desirable configurational results. Thus, the task of creative synthesis is only to generate configurations that, through evaluation, will enlighten the identification of the next interesting conceptual issue. Each new configuration does not have to be a good solution, only one that will further direct the discovery process. The final outcome of the design process is a configuration that has evolved through the application of many repeated PI–CS–E cycles and represents a refined and viable conceptual design.

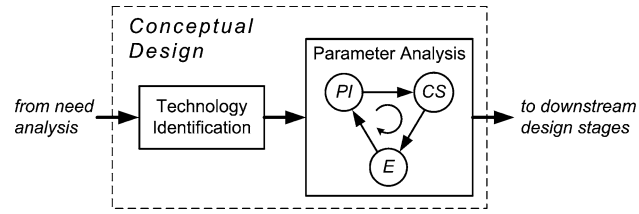



**Fig. 7** A *technology identification* stage is added to the prescriptive model of parameter analysis

A realistic model of the design process should have both divergent and convergent thinking components, and this is accomplished in the parameter analysis methodology too. The mental processes in concept space, namely PI and part of E (see Fig. 6), are convergent because they focus the design progression by identifying one or a few weaknesses and conceptual-level issues. CS and the other part of E tend to be more divergent, as there usually are many ways to realize a concept and more than one weakness that is discovered during evaluation.

Real design processes are rarely linear in nature, and parameter analysis is no exception. It may seem that a complete design process can begin with a certain concept in a PI step, proceed through a sequence of PI, CS, and E steps, and terminate with an E step that says the design is complete. However, failures of different types may occur in the process, and even if everything proceeds as expected, there is often a need to repeat the process to generate several alternative designs, not just one. For these reasons, it was necessary to add a stage, called *technology identification,* to the conceptual design process that precedes parameter analysis, as shown in Fig. 7.

Technology identification refers to the process of looking into possible fundamental technologies that can be used for the design task at hand, thus establishing several starting points, or initial conditions, for parameter analysis. Often, several such core technologies, or physical principles, can be used in a particular design. Technology identification plays a similar role to functional decomposition and morphology in systematic design, except that it focuses on the working principles for the *most important* function

of the designed artifact, and ignores the less significant aspects. A cursory listing of each candidate technology's pros and cons is usually all that is required at this stage to allow the designer to pick the one that seems most likely to result in a successful design. If a parameter analysis process reaches a dead-end at some point, and it is realized by the designer that a major change is required, not merely backtracking to an earlier decision point and redoing the process, then another technology identified at the outset can be used as the new starting point for parameter analysis. And if the development of several alternative conceptual designs is desired, they can all be developed from different such core technologies.

## 4 Simulated conceptual design of the bilge pump by parameter analysis

To demonstrate the generation and development of concepts with parameter analysis, and contrast this methodology with functional decomposition and morphology, we hypothesize the design process elaborated below for the bilge pump example of Sect. 2. It begins with a technology identification step, wherein the designer realizes that the actual pumping of water out of the bilges of boats is a relatively easy task and that the main problem is to capture the required energy from a natural source. He/she then evaluates several possible energy sources, such as solar, wave, and wind energies, even energy from falling raindrops. Each of these is evaluated by listing its advantages and drawbacks.

Solar energy is not always available, so batteries will be used to store electrical energy and drive a motor to power a pump. The cost of solar panels plus the rest of the system may be prohibitive. Wave energy can be captured directly from the waves with a float-like device, or using the boat's motion to energize a mass. The boat will move horizontally and vertically. It is not trivial to capture this energy, but it may work. Wind energy is relatively easy to capture but may require a large turbine to produce enough power. The size of the energy-capturing device may be problematic. Falling rain drops have kinetic energy when they hit the boat, but it seems there will not be enough energy to produce the required pumping power. Besides, how will this energy be captured? The designer decides that the most likely candidate to result in a viable design is wave energy, captured from the boat's motion relative to the mooring post. If this fails, the boat's vertical motion or the wind energy option will be tried.

Now that the boat's motion has been selected as the most promising starting point; this chosen technology serves as the initial parameter, or concept, in the parameter analysis process described in Fig. 8.

This example shows how technology identification is used to generate initial core concepts that address the main and most difficult issue of the design, as opposed to functional decomposition and morphology's treatment of *all* functions at the same time and at the same level of importance. Also demonstrated is the nature of the concept development process, in which attributes are added to the design and changes are made to the evolving configuration until judged by the designer to be complete. Throughout the development process, evaluations are repeatedly applied to check the design for proper functioning and against the requirements, new conceptual-level issues, consisting mostly of a function that needs to be fulfilled and an idea of how to do it, are recognized and implemented as configurations, with quantitative data being added when necessary.

## 5 Generation of innovative concepts: case study of aerodynamic decelerators

The hypothetical parameter analysis process of the previous section demonstrated a routine design problem that did not require any breakthrough or highly innovative ideas. Consider now the following design task. It is desired to design the means for deploying a large number of airborne sensors for monitoring air quality and composition, wind velocities, atmospheric pressure variations, and so on. The sensors are to be released at altitudes of about 3,000 m from an under-wing container carried by a light aircraft. Typically, some 500 sensors would be discharged, and they should stay as long as possible in the air, with the descent rate not exceeding 3 m/s (corresponding to the sensor staying airborne for over 15 min). Each sensor contains a small battery and radio transmitter and is packaged as a $\phi 10 \times 50$ mm cylinder weighing 10 g, with its center of gravity located about 10 mm from one end. It is necessary to design the aerodynamic decelerators to be attached to the payload (the sensors), and the method of their deployment from a minimum weight and size container.

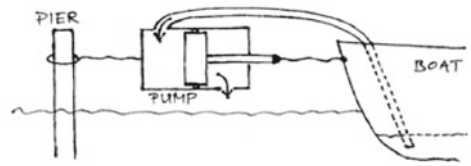
During the need analysis stage, some preliminary calculations showed that at $Re > 10^4$ (this Reynolds number corresponds to several tens of millimeters characteristic length and a velocity of 3 m/s), the drag coefficient $C_D$ of a parachute shaped decelerator is about 2, so to balance a total weight of 12–15 g (10 g sensor plus 2–5 g assumed for the decelerator itself), the parachute's diameter will be $\sim$150 mm. If the decelerator is a flat disk perpendicular to the flow, the $C_D$ reduces to $\sim$1.2, and if it is a sphere, then $C_D \cong 0.5$, with the corresponding diameters being about 200 and 300 mm, respectively.

It also became apparent at that point that such large decelerators would be difficult to pack compactly in large numbers, that they should be strong enough to sustain

**Fig. 8** Hypothetical parameter analysis processes for the bilge pump concept development. *PI* parameter identification, *CS* creative synthesis, *E* evaluation

*PI: Use the boat's horizontal motion on the waves to move a piston in a cylinder for generating pumping action.*

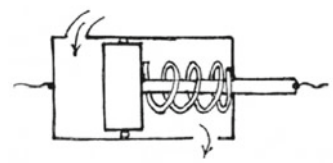
*CS: A piston-in-cylinder type of reciprocating pump is attached by ropes between the pier and the boat. When the boat moves away from the pier, the piston creates suction on one side and pressure on the other, so the bilge water can be pumped.*




*E: What happens when the boat moves towards the pier? The ropes can't transmit compression, so how will the piston return?*

*PI: A spring can be used for a restoring force.*

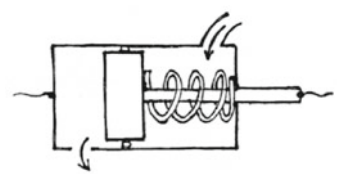
*CS: A spring is added so that it's compressed when the boat moves away from the pier, and released on the way back.*



*E: The boat's movement away from the pier may be too slow to produce enough suction and overcome the spring's resistance.*

*PI: Capture all the boat's motion as elastic energy and use it for pumping water when the spring is released.*

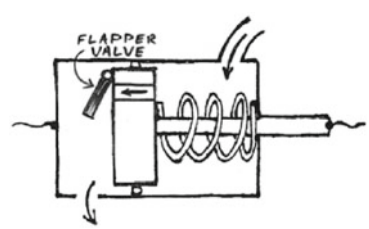
*CS: The suction and ejection sides of the pump are reversed. When the boat moves away from the pier, the spring is compressed. When the boat moves towards the pier, all the spring's energy is used for pumping water. If the stroke of the piston is set to 50 mm and its diameter to 30 mm, then the volume displaced per stroke is ~35 cm$^3$. The required throughput is about 8 L/hr ≈ 2 cm$^3$/s. The pump will actually move water only when the spring returns the piston, so let's assume this happens during 1/4 of the time. A complete stroke of the piston is required every 4 to 5 seconds.*



*E: The dimensions of the pump are small enough and the throughput satisfactory, but the water entering the pump needs to be transferred to the other side of the piston so it can be ejected.*

*PI: Add a one-way valve in the piston to allow passage of water when the piston moves to the right.*

*CS: A flapper valve is added:*




aerodynamic loads, particularly during their deployment, when the relative velocity between them and the surrounding air is high, and that being disposable, they should be relatively cheap to make and assemble. Further, the sturdier the decelerator is made; chances are that it will also be heavier. And the heavier it is, the larger it will have to be in order to provide enough area to generate the required drag force.

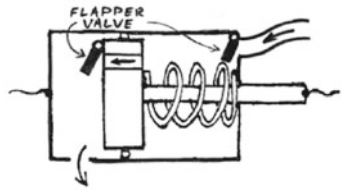
A functional decomposition and morphology process led student design teams to propose a conventional parachute (i.e., made of flexible material so that it can be folded for packing), "rigid parachute" (pyramid or conical shape, for example), and balloon filled with lighter-than-air gas (utilizing both its buoyancy and aerodynamic drag) for the function of "provide aerodynamic resistance" (see Fig. 9). Another function, "allow compact packaging in a container," resulted in concepts such as "shapes that are enclosed in small volumes," "shapes that can nest one inside the other" and "folding structures."

**Fig. 8** continued

*E: When the piston moves to the right, there may be back-flow from the pump to the boat.*

*PI: Add a one-way valve to the pump's inlet.*

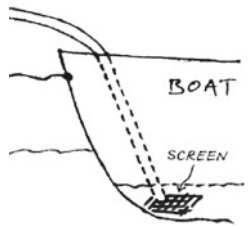
*CS: Another flapper valve is added:*




*E: Debris/impurities may be pumped and clog the pump or interfere with the valves.*

*PI: Filter the water at the hose inlet.*

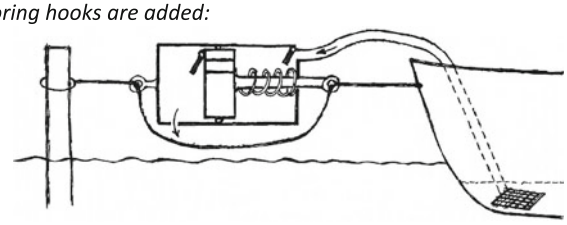
*CS: A screen is added:*




*E: Cutting the rope between the boat and pier to install the pump is difficult and inconvenient.*

*PI: The rope doesn't have to be cut. The pump can be connected to 2 points on the rope with a slack between them.*

*CS: Suitable anchoring hooks are added:*



*E: This concept seems to work; the conceptual design is complete.*

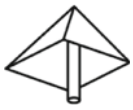
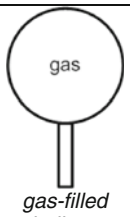
| Subfunctions | Subconcepts | | |
|---|---|---|---|
| Provide aerodynamic resistance |  *flexible parachute* |  *rigid parachute* |   *gas-filled balloon* |
| Allow compact packaging | *shapes enclosed in small volumes* | *nesting shapes* | *folding structures* |

**Fig. 9** A portion of the morphological chart for the aerodynamic decelerators

The combination concept chosen by one team for further development consisted of a conical rigid parachute (chosen because of its high drag coefficient), but because it occupied a large volume and could not provide the nesting property, folding was selected instead. For the structure to fold, it had to be made of a flexible sheet material stretched over rigid members, with many hinges, sliding contacts, and an opening mechanism, just like an umbrella (Fig. 10). This resulted in a very complex design (with some accompanying reliability issues), which did not lend itself to automated manufacturing or assembly and consequently, to a potentially prohibitive cost. Although the designers went on and refined the concept, even built and tested a prototype, this did not prove to be a good solution.

Other design teams were assigned the same task, but using parameter analysis. The complete design processes will not be presented here, just the highlights. One team started with the concept of a rigid parachute. They chose a high $C_D$ shape (in the parameter identification, or PI, step) of a hemisphere and determined the relationship between the drag force produced and the size, or diameter of the decelerator (creative synthesis, CS). In the evaluation (E) step, they recognized the fact that the configuration did not allow compact packaging (while hemispherical shapes can be nested inside each other, the sensors themselves

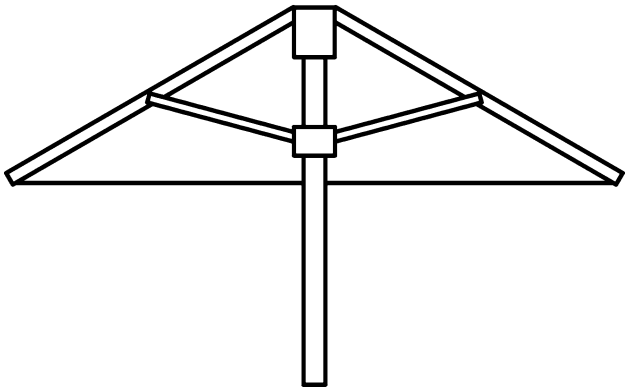


**Fig. 10** Schematic of a proposed umbrella-type decelerator

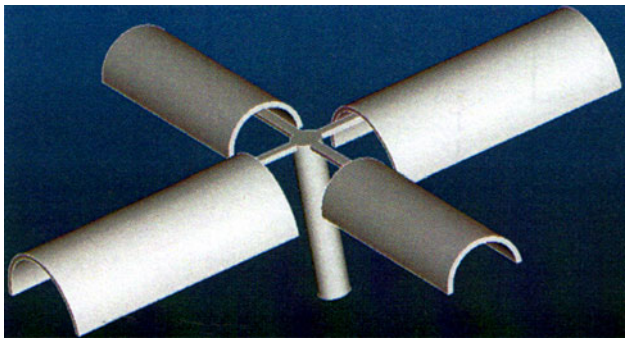


**Fig. 11** A proposed design with two pairs of "wings" that can fold around the cylindrical sensor to allow compact packaging

prevent this), so the next parameter (PI) was "a high $C_D$ shape that can be folded around the cylindrical sensor in a simple way." Note that this parameter, or concept, combines three functional issues: providing aerodynamic resistance, allowing compact packaging, and being simple. This is in contrast to systematic design's treatment of each function separately. The configuration (CS) proposed for realizing the last concept is shown in Fig. 11.

Another design team chose the flexible parachute concept to start with (PI). Sizing the parachute (CS) led them to realize that the payload's light weight might not guarantee opening of the folded parachute and that the cords could also tangle during deployment (E). This resulted in re-examining the physics of the problem as follows (PI). They recognized the fact that the design actually called for dissipating the potential energy of an object released at an altitude. Aerodynamic drag opposite to the descent direction (i.e., a force pointing vertically upward) would dissipate energy by frictional work that depended on the size of the decelerator. However, if energy dissipation by frictional (drag) work was the dominating physics, then the physics of work should be studied carefully. Work is the product of force and distance. In vertical descent, the distance is the altitude, so the focus in the design was on creating a large vertical drag force, one that was equal to the weight of the falling object. Such a large force dictated a large size decelerator. But what if the distance could be made longer? Then it would be possible to dissipate the energy by a combination of long travel distance and small force, and the latter might equate to a smaller object that could be packed compactly in large quantities. And so the concept of a "glider" was born. Two configurations for realizing this last concept are shown in Fig. 12. They were further refined to introduce an imbalance in the design so that when deployed, the glider would follow a spiral trajectory with a diameter of approximately 30 m.

Note that the glider solution is very different from the initial concept. In systematic design, starting with the "flexible parachute" concept would most likely yield a final design that can be quite refined, but still clearly a type of folding parachute. In parameter analysis, on the other hand, the glider concept emerged from the parachute concept through high-level conceptual reasoning *during* the development of the concept.

Another design team also realized that the physics of the problem did not necessarily require a simple drag-force device (i.e., a parachute), and through energy considerations decided to attempt dissipating additional potential energy of the falling object by forcing it to rotate in a windmill style (PI). Figure 13a shows a model made on a rapid prototyping machine of a skeleton with a thin plastic film (Saran Wrap) stretched and glued onto it, and a weight simulating the sensor attached below (CS). The rotating wings, or propeller blades, act against air resistance in the horizontal plane in addition to the vertical drag. A rotating device of this sort probably could not have emerged from systematic design had the concept of a "windmill" or "autogyro" not been identified at the stage of searching for solution principles.

Interestingly, rotating wings have also been proposed by design teams who used analogies to nature. The physical model of the decelerator of Fig. 13b was inspired by the Samara fruit (as found on elm and maple trees, for example).

This case study demonstrated how parameter analysis allowed innovative concepts to be discovered *during* the process of concept development even when starting with not-so-good ideas. The "design space" was expanded while designing, with the help of new and deeper understanding of the task and its potential solutions.

## 6 The dual role of capturing design rationale

Parameter analysis was shown in Sect. 4 to constitute a methodological process of developing a concept, which is

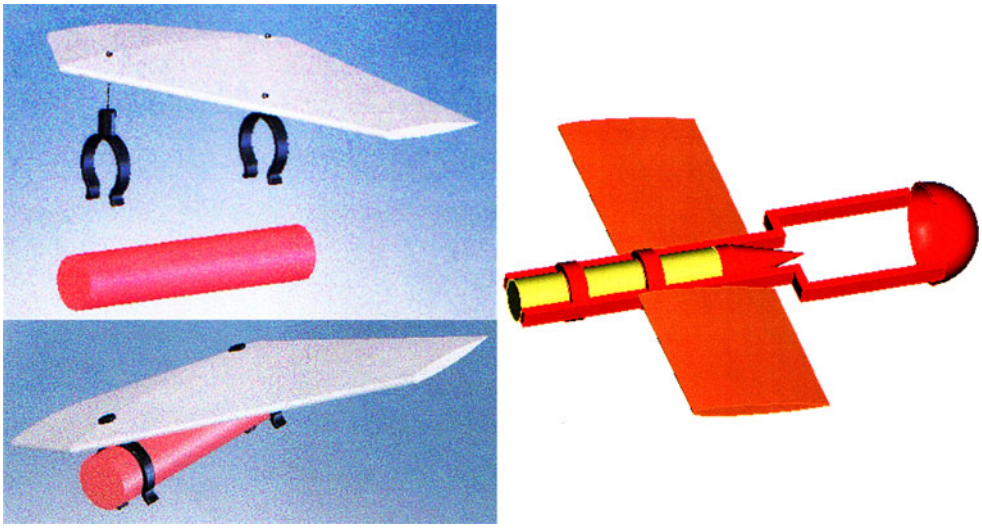


**Fig. 12** Two "glider" designs showing the simplicity of the concept

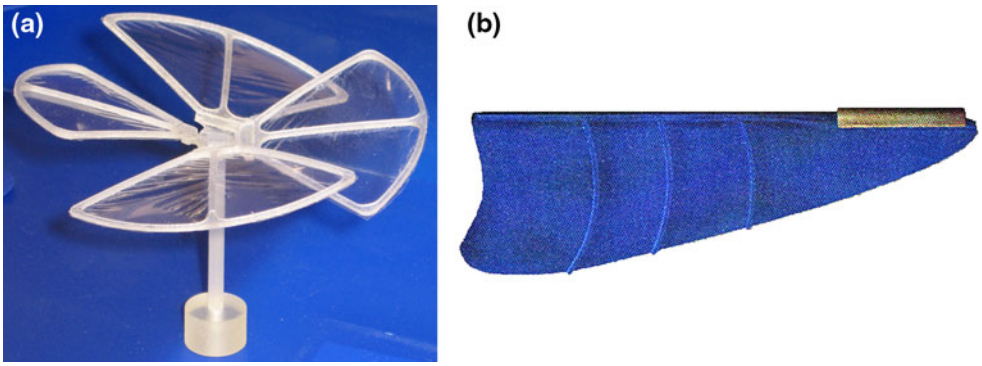



**Fig. 13** **a** A prototype made for testing the "windmill" or "propeller" concept, **b** a model of rotating decelerator inspired by a winged Samara fruit

often missing in the formal presentations of functional decomposition and morphology case studies. In addition to helping the designer in this way, there is an added benefit to using parameter analysis: creating a "trace" of the thought process that captures the rationale of the design. This can be used in two settings: industrial and academic. Much of everyday design work in industry is in fact redesign, so companies can utilize prior knowledge effectively even when team members, the environment and technology change, by capturing and maintaining the historical account of the design process. Similarly, when educating and training designers, such records are very useful in analyzing and studying the design reasoning and reflecting upon the design process.

The parameter analysis process, as demonstrated in Fig. 8, provides a full account of why a product was made the way it was, including the reasons and justifications of design decisions, other alternatives considered, tradeoffs made, why some ideas were rejected, even allowing the identification of design mistakes (Kroll and Shihmanter 2011). Consider for example the conceptual design of the bilge pump shown in Fig. 14, which is one of the several designs demonstrated by Otto and Wood (2000). If functional decomposition and morphology were used for this conceptual design, the record kept would indicate that this concept was based on capturing wind energy with a propeller, transmitting it with gears and a crankshaft to a reciprocating pump that employs flapper valves to control the flow direction, tubes for moving the bilge water, and a screen to filter them.

In contrast, a concept development process with parameter analysis, similar to that of Fig. 8, might also show that a propeller was chosen after the option of "air cups" was evaluated quantitatively and shown to result in too large a structure; that the propeller and pump were roughly sized to provide the power necessary for the required flow rate and pumping head; that the use of a horizontal wind turbine has not been considered by the designer at all, something that might have eliminated the use of the bevel gears; and that the choice of a reciprocating

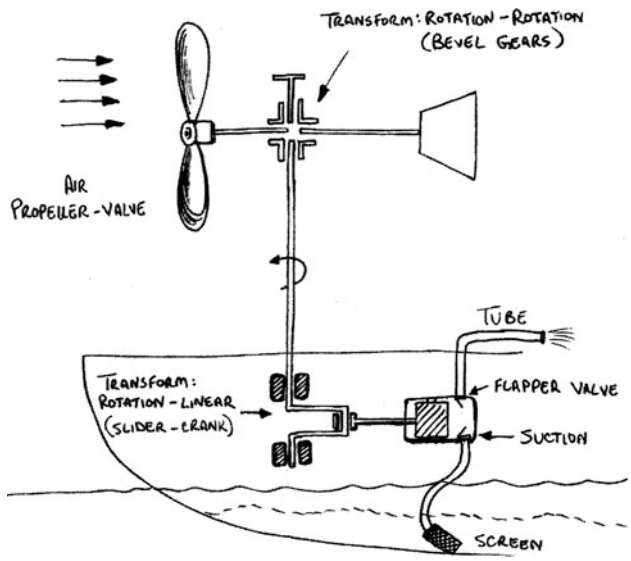



**Fig. 14** One concept for the bilge pump that uses a wind turbine and reciprocating pump (Otto and Wood 2000)

pump was not satisfactorily justified, so a rotary pump might have been a better choice overlooked by the designer. This added wealth of information is clearly very beneficial when examining a design such as in Fig. 14 for the purposes of understanding and reusing its rationale.

## 7 Using C–K Theory for comparing the methodologies

C–K Theory was first introduced about a decade ago (Hatchuel and Weil 2002; Hatchuel and Weil 2003) and has gained considerable interest in the design community. It is a general descriptive model with a strong logical foundation, resulting in powerful expressive capabilities. C–K Theory has been studied in industrial (e.g., Hatchuel et al. 2004) and academic contexts, including as a methodology for scientific discovery (Hatchuel et al. 2005; Elmquist and Segrestin 2007), and is thoroughly described in Hatchuel and Weil (2009). The theory models design as interplay between two spaces, Concept (C) space and Knowledge (K) space, and four operators that are used to describe movement between and within the spaces: C → K, K → C, K → K, and C → C.

Space K contains all established, or true, propositions, which is all the knowledge available to the designer. Space C contains "concepts," which are undecidable propositions (neither true nor false) relative to K. Concepts define unusual sets of objects called C-sets, that is, sets of partially unknown objects whose existence is not guaranteed in K. Design processes aim to transform undecidable propositions into true propositions by jointly expanding spaces C and K through the action of the four design operators. This expansion, sometimes referred to as partitioning, continues until a C-set becomes a K-set, that is, a set of objects that is well defined by a true proposition in K. It was shown in the literature that expansion of C yields a tree structure, while that of K produces a more chaotic pattern.

Examination of parameter analysis in light of C–K Theory reveals that both concept space and configuration space of the former are contained inside the latter's C-space. This becomes apparent when the meaning of "concept" in C–K Theory is understood to be synonymous with the design artifact, including ideas, the hardware, and other attributes. As long as the design is not finished (i.e., not proven true or false), it stays in C-space; when finished or proven false, it becomes "knowledge" and moves to K-space. This notion of "concept" is very different from the parameter analysis use of "parameters" as representing entities at the conceptual level, and the separate representation of the designed artifact as an element of configuration space.

Figure 15 is an attempt to fit together parameter analysis and C–K Theory. It shows not only that this can be done, so parameter analysis as a practical design methodology supports and empirically validates C–K Theory, but also hints at interesting new possibilities. First, it may give new meaning to some of C-K's operators. Arrow *I* in Fig. 15 symbolizes the generation of new knowledge by research, consultation, etc. (K → K operator). Arrows *II* and *III* are K → C operators representing the use of knowledge to synthesize a new object and to evaluate the evolving design, respectively. Arrow *IV* is a C → K operator that denotes the generation of new knowledge by creating a new object, as happens when a design process succeeds and the "concept" is proven true. Arrow *V* is a C → C operator that stands for implementing an idea in hardware, while the two C → C operators of arrows *VI* and *VII* are the generation of a new idea from an evaluation of previous configuration or directly from another idea, respectively.

A second interesting possibility is to divide C–K's C-space into subspaces corresponding to concept space and configuration space in parameter analysis, thus allowing a more detailed model of the design process than with the general notion of "concepts" in C–K Theory. Thirdly, the explicit representation of knowledge in C–K (K-space) can enhance parameter analysis and our understanding of design in general by classifying the elements of K-space into various types, such as knowledge of the problem domain, knowledge of related disciplines, knowledge of the design process (i.e., meta-knowledge or reflection) and the designer's "bag of tricks," as discussed in the next section.

The fact that the whole parameter analysis process is depicted in Fig. 15 as being contained in C-K's C-space

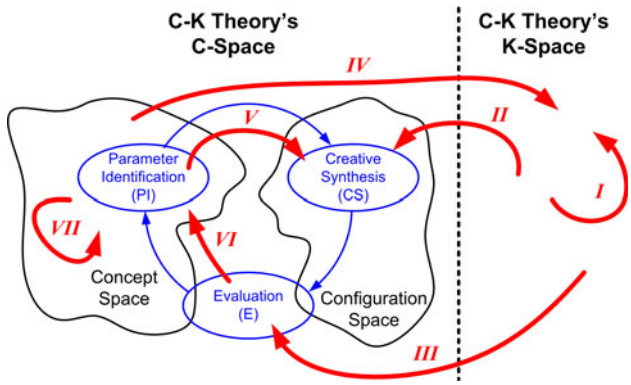



**Fig. 15** Fitting together parameter analysis and C–K Theory. New meaning can sometimes be assigned to C–K's operators, depicted by the *arrows* with *Roman numerals*, as elaborated in the text

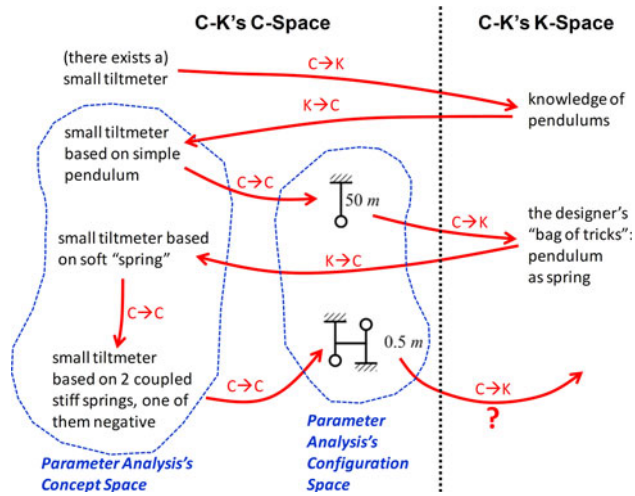



**Fig. 16** The first few steps in the tiltmeter design process on a combined parameter analysis and C–K Theory diagram. All C–K's "concepts" are propositions of the form "there exists an object…" The *question mark* at the *bottom right* denotes checking the logical status of the last configuration, and moving it to K-space if true or false

may seem surprising at first, if misinterpreted to mean that no knowledge is used when designing with parameter analysis. However, the following arguments should support this conclusion:

(a) The parameter analysis model consists of only two spaces, concepts and configurations, that both represent the evolving design artifact. Obviously, knowledge is required and used by parameter analysis, but the model does not include the knowledge items or excursions to and from a knowledge space. Therefore, none of the spaces of parameter analysis can be drawn to overlap C–K's K-space.

(b) C–K Theory's use of the notion of "spaces" is very different from the understanding of this term in parameter analysis and many other design methodologies. The conventional usage of "space" is as a collection of entities that belong to the same class or type. For example, the FBS model (Gero and Kannengiesser 2004) uses the space of Functions, space of Behaviors and space of Structures to group together each entity type. Similarly, parameter analysis puts all conceptual-level issues raised and handled during the design process in concept space, and all hardware realizations and embodiments of the artifact in configuration space. In contrast, a "concept" in C–K Theory means both the ideas and their implementation, and this entity often inhabits not just the C-space, but also the K-space. This happens when the concept's logical status changes to true or false, that is, when the designer judges the evolving design to be realizable (=true) or proves its infeasibility (=false).

(c) Parameter analysis is a pragmatic model, where it is understood that during most of the design process, the work should be considered tentative (or "undecidable" in C–K terms). The conceptual design process is considered finished only when a configuration has been specified that is judged by the designer to work well and satisfy all the requirements. The step of declaring that the artifact ("concept" in C–K) is now logically true and therefore becomes an item of knowledge, which corresponds to the final evaluation in parameter analysis (see, for example, the last line in Fig. 8), does not explicitly appear in the schematic model. In C–K, however, because of its formal logic foundation, this kind of C → K move (arrow *IV* in Fig. 15) is indispensable.

Returning to the tiltmeter design example from Sect. 3, it is possible to demonstrate the thought process on a combined parameter analysis and C–K Theory diagram, as shown in Fig. 16.

The expansion of C-space is the fundamental mechanism of generating new ideas in C–K Theory, and it is therefore of great interest to model this tree structure, as shown in Fig. 17 for the tiltmeter example. The diagram can be made while designing, providing insight on the so-called solution space and even pointing the designer in new directions, or as a reflection on the design process after completing it.

How can we compare parameter analysis to functional decomposition and morphology in terms of C–K Theory? While a rigorous and complete comparison is beyond the scope of this paper, we can still state some differences. As mentioned in the Introduction, methods for conceptual design attempt to reduce the amount of unknown to the point that what is left is easily handled in subsequent stages by the available knowledge. However, the methods

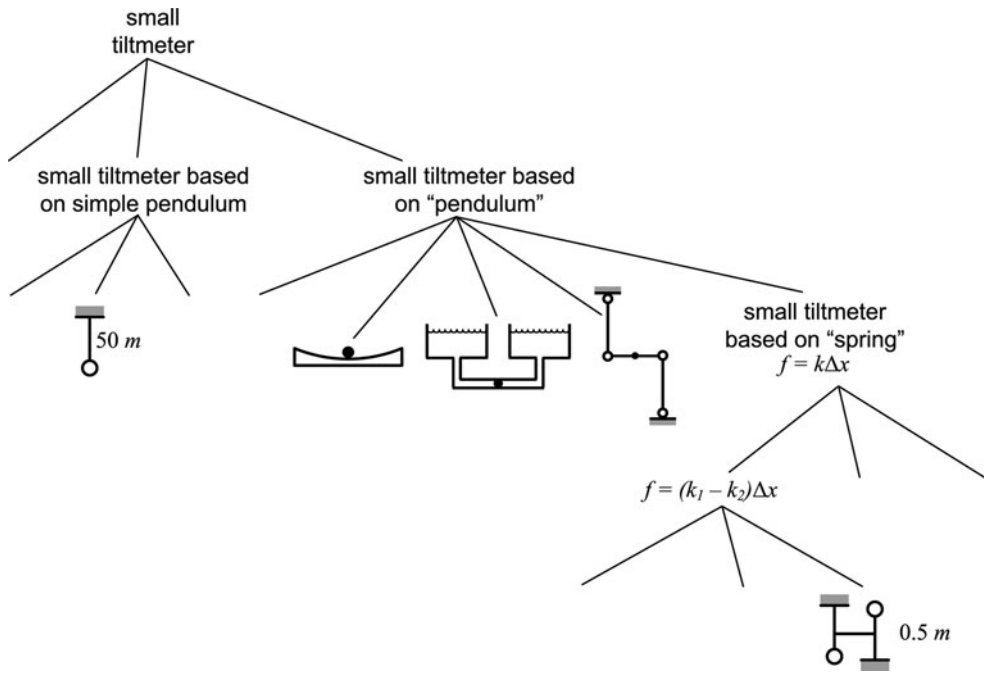



**Fig. 17** Expansion of C-space by the first steps in the tiltmeter design example. Some of the concept sketches at the *center* of the diagram are unexplored possibilities mentioned in chapter 4 of Kroll et al. (2001)

discussed here use different strategies for doing that. Functional decomposition and morphology assumes that the artifact's functionality can be defined independently from its realization. In C–K terms, this means that K-space is assumed constant and stable. The method then attempts to add as much knowledge as possible and as quickly as possible, to reduce the unknown. The main mechanism for doing it, in C–K terms, is *restrictive* partitions, as the attributes added to the concept (to satisfy all the required subfunctions) are all known in K. The only *expansive* partition (adding something original that changes the identity of the object) that takes place is by combination (choosing different items in the morphological chart for integrating into an overall concept).

Parameter analysis, on the other hand, focuses on the critical conceptual issues first and only later addresses the other issues, among them new functionalities that depend on the currently attempted realization. It not only delays the reduction of the unknowns related to the less important aspects but relies heavily on exploration and expansion of the knowledge. These K-expansions are necessary to validate the *expansive* partitions in C-space as solutions to the design task or for leading to further *expansive* partitions. For example, in the decelerators example of Sect. 5, parachutes and balloons represent existing knowledge about means of slowing down the descent of an object. Knowledge of gliders may also exist, but not as a decelerator, so functional decomposition and morphology did not consider using it. Parameter analysis indeed started with the available knowledge of parachutes and balloons, but these concepts, generated by restrictive partitions in C, led eventually to the expansive partition that included "energy dissipation by small force over long distance." This, in turn, was developed further and validated by a K-expansion regarding gliding properties of aircraft. Finally, the "glider as decelerator" solution was added as a new piece of knowledge to K, increasing the designers' competency in addressing similar problems in the future.

The key conclusion from the comparison is therefore that functional decomposition and morphology does not seem to use K-expansions, only C-expansions, while parameter analysis uses both. Hatchuel and Weil (2009) and Reich et al. (2012) showed that creative design necessarily requires both types of expansions. When confronted with a new design situation, in which the functionality of the solution is unknown to a large extent and innovation is necessary, parameter analysis presents a useful strategy. But, after becoming familiar with the problem domain and having established the knowledge necessary for its solution (which turns the design task into a more routine one), perhaps by using parameter analysis, functional decomposition and morphology can help in the systematic generation of the best combination of the individual known solution elements.

## 8 Implications of parameter analysis on training designers

Parameter analysis started as a methodology for training innovators (Li et al. 1980) and has progressed into a prescriptive model of conceptual design. Its emphasis on the

identification of conceptual-level issues and relationships ("parameters"), synthesizing configurations in response to the concepts, and continuously evaluating the evolving design to point the way to the next conceptual-level aspects are all fundamental notions in design thinking. Engaging students and practitioners in the process of parameter analysis is thus equivalent to improving the skills and capabilities of athletes or musicians through ongoing training.

Experimental studies of design fixation, from Jansson and Smith (1991) to recent efforts such as Linsey et al. (2010), demonstrated that introducing example solutions can cause fixation and reduce creativity. This may suggest that training designers through case studies may not be very effective and may even hinder their ability to innovate. Many design textbooks are filled with rules, principles, and guidelines, all accompanied by such potentially fixating examples. Parameter analysis, on the other hand, fosters a coaching approach called *technology observation* (Kroll et al. 2001, chapter 11), which is the continuous process of studying and analyzing existing technological products in order to understand *how* and *why* rather than merely *what* has been done by others. By observing technology in this particular way, with time the designer will accumulate a knowledge base, or bag of tricks, that consists of understanding the underlying concepts of configurations and phenomena, as opposed to details of specific designs. And when applied to creating a new design, these concepts will allow the designer to draw useful analogies and gain insight into the task at hand.

The bag of tricks may well be what distinguishes an experienced creative designer from the novice. It includes the ability to look at a design task and tell the really difficult issues from the straightforward ones; for example, realizing that capturing natural energy was the main problem with the bilge pump example, as opposed to producing pumping action, moving the water, or filtering them. The bag of tricks should also contain the skill of looking at a situation in a different way, such as "pendulum as spring" in the tiltmeter example, and abstraction to identify the dominant physics, as with the relationship between force and distance in the frictional work done in the aerodynamic decelerators example.

The important aspect of using parameter analysis as a teaching and training methodology is that it develops the innovative skills of designers by providing a prescription that is close to the natural thought process. Support for this last assertion can be found in the Zigzag problem-solving process, which is based on the Myers-Briggs Type Indicator from psychology (Lawrence 1993). This four-step iterative process starts with "Sensing" to identify and analyze the problem, continues with "Intuition" to develop alternative solutions and "Thinking" to analyze them and identify their pros and cons, and concludes with "Feeling" to apply judgment and make a decision (Daigle et al. 1999; Chang and Chang 2000; Lewis and Smith 2008). Although at the stage of training the designer it is beneficial to force him or her to produce a written record similar to Fig. 8, it is obvious that with enough practice, the parameter analysis way of thinking becomes a second nature and the seemingly "forced march" in writing is no longer necessary.

## 9 Discussion

Design education and practice are tightly connected. What we teach in a capstone design class is what the students carry over to usage after they graduate. Even industry-specific practices that can often be found in large companies probably originate from university design classes and engineering design textbooks. It is therefore a sort of a paradox that many design educators who may not believe that systematic design's functional decomposition and morphology always works, still use this method in the classroom. The likely explanation to this phenomenon is that the method is so simple and logical: break down the main function of the desired artifact to elementary functions, write down the working principles by which each function can be fulfilled, and now just combine these principles and you get a conceptual design.

However, the notion that this overly "mechanized" process is at the heart of design may be somewhat misleading. It implies that no "spark of ingenuity" is necessary for innovation, and it trivializes the essence of creative design. We can only speculate that the reason why this approach to design teaching has become so prevalent in our universities may be traced to two developments from the late 1970s and early 1980s. First, there was a realization in the US that it was increasingly losing its competitiveness in the industrial markets to other countries. This led to examining the way design should be taught at universities and realizing that capstone design classes were needed. Around the same time, almost no one knew what methods should be taught in these classes, and the first English translation of Pahl et al. (2007), in 1984, soon filled this gap. The second development leading to the ubiquity of functional decomposition and morphology was the belief that computer programs with artificial intelligence, using problem-solving and search strategies, could one day carry out design tasks if the method is systematic, logical, and of a mechanical nature.

Parameter analysis has been shown in this paper to include aspects of design activities that are essential. Innovative design should be considered a discovery process and not a search over an existing solution space. This means, for example, that it is impossible to list all the functions of a design without regarding any particular

solution. In the tiltmeter example, the need for frictionless hinges only emerged when a concept that uses hinges was developed. Parameter analysis emphasizes that conceptual reasoning is required to support every configurational attribute of the evolving artifact, while focusing on one or a few dominant issues at a time during the development of a design. Moreover, it stresses looking at problems in different and new ways, thus tightening the partnership between analysis and synthesis. Finally, parameter analysis also shows that good design is a synthesis of a series of good ideas, or concepts, not just one.

These attributes of parameter analysis comply with modern notions of design as co-evolution of the problem and solution spaces (Maher 2001; Dorst and Cross 2001) and the FBS (function-behavior-structure) model (Gero and Kannengiesser 2004). Resemblance of parameter analysis to some of the features of the TRIZ family of creativity methods (Altshuller 1984; Reich et al. 2012) should also be noted. For example, the basic process of identifying a specific problem with the design, generalizing it into a generic problem, looking for a possible matching generic solution and finally, deriving a specific solution are closely related in spirit to parameter analysis's cycle of evaluation of an evolving configuration, generalizing to identify a conceptual solution, and particularization of the concept into a new specific configuration (Fig. 6). Moreover, some of TRIZ's tools, such as the contradiction matrix and the 40 inventive principles, may also be looked upon as the designer's "bag of tricks" in parameter analysis. Most TRIZ case studies in the literature demonstrate how a single innovative idea can be found and applied to solve a difficult design problem, and less emphasis is put on demonstrating an evolutionary development of a concept that involves many cycles and ideas, as is done with parameter analysis. This hints at the future possibility of combining the two methodologies.

Support for the cyclic, evolutionary concept-configuration-evaluation thought process that underlies parameter analysis can be found in other research efforts. In the CPM/PDD approach to modeling design artifacts and processes (Weber 2005), the iterative process takes place by moving between the structure of the product (C = characteristics) and its behavior (P = properties), with the latter being the main "driver" (PDD stands for Property-Driven Development). Cross (2006) describes the study of three innovative designs by expert designers—engineering, product and race car designers—who do not seem to use methods similar to functional decomposition and morphology at all. Rather, they all identify quickly the crux of the design task in conceptual-level terms (e.g., a backpack to be mounted on a bike should be as low as possible), generate an approach to solving it (mount the backpack on the rear wheel), examine it (putting the weight in the rear is better than in the front when going downhill, but it might still cause wobbling and therefore, stability issues), modify it (the backpack will still be mounted in the rear of the bike, but the mounting frame will have to be very rigid), and so on.

Perhaps the strongest evidence to designers' adopting a thought process similar to parameter analysis can be found in the reports on the DRed rationale capture system (Bracewell et al. 2009). This software tool is based on the more general IBIS (Issue-Based Information System) concept (Kunz and Rittel 1970), which was an information management tool aimed at enabling problem solvers to model and communicate their solution process by recording the issues addressed, the options considered and their pros and cons. DRed uses a directed graph representation to capture this information in an elaborate way by allowing, for example, the distinction between open, resolved, insoluble, and rejected issues. While designing, issues are usually the problems associated with a proposed solution; alternatives considered are possible cures; and the pros and cons listing is their assessment. Although this scheme does not explicitly differentiate between solution concepts and their implementation, as does parameter analysis with its concepts versus configurations, the overall reasoning and design progression follow very similar logics.

Parameter analysis has also been shown in this paper to provide empirical validation of the C–K Theory of design, thus obtaining a scientific support. However, it should be realized that C–K Theory is still undergoing development. Kazakçi and Tsoukias (2005), for example, proposed adding another space to the model, the environmental space E. Future work on both parameter analysis and C–K Theory may well lead to further modification and refinement of both models. In particular, C–K's explicit modeling of knowledge expansion could contribute to better understanding of parameter analysis. Other future enhancements of parameter analysis may include adding clear representations of functional and behavioral issues, and providing means to accommodate design activities such as generating of requirements while designing, and selecting among alternatives.

Looking at conceptual design from the C–K Theory perspective allowed us to show that the main difference between functional decomposition and morphology and parameter analysis is their area of relevance. Only parameter analysis is applicable in new situations, when the knowledge may not exist and needs to be searched for and discovered. This expansion of the knowledge space is driven by those conceptual-level issues we call "parameters." Functional decomposition and morphology cannot be considered a creative method in C–K terms but has its strengths when dealing with more routine tasks. An interesting possibility for a future study would be to combine both methods: develop a conceptual design strategy that

uses parameter analysis first, when the extent of the unknown is large and expansion of the knowledge is needed and depends on the expansion of concepts, followed by functional decomposition and morphology for the systematic application of this knowledge.

Besides the difference in area of relevance, the other comparison criteria mentioned in the Introduction were the process efficiency and innovativeness and robustness of the results. Functional decompositions and morphology clearly uses a less focused, breadth-first approach to developing concepts, generating many alternatives, of which some may be useless. Parameter analysis, on the other hand, works depth-first and is therefore more efficient. It resembles a process whereby a sort of virtual prototype (the configuration) is developed quickly to allow evaluation and further refinement. Parameter analysis also produces more innovative and robust solutions, because it encourages discovery of new knowledge that did not exist or seem relevant at the beginning of the process, and due to the fact that it continually forces ideas to be incorporated as configurations in the evolving artifact, followed by evaluation. In contrast, functional decomposition and morphology can derive an innovative solution mainly by novel combinations of known solutions, and it lacks an incremental development process accompanied by quantitative analysis to ensure the robustness of the solution.

## 10 Conclusion

Functional decomposition and morphology, as systematic design's way of doing conceptual design, is easy to teach and learn, so many contemporary design textbooks have adopted it. However, some of the drawbacks of the method as outlined in this paper point at the need to revise our perception of the best methods for teaching and practicing design. Indeed, the design examples used in this paper served to illustrate the main points, and further research accompanied by rigorous experimentation will be needed to generalize and validate the conclusions. Yet, the theory-based comparison showed that parameter analysis offers many benefits as a methodology for design. The mechanical nature of the procedure of searching for existing concepts in systematic design can yield innovative solutions mostly by way of creating new combinations. Parameter analysis, on the other hand, supports a much deeper thought process to discover new, creative concepts, which in turn drive the exploration of new knowledge. It therefore constitutes an alternative for both teaching and practicing innovative design.

**Acknowledgments** The insightful comments of the reviewers contributed significantly to improving this paper and are gratefully acknowledged, as is the partial support of this work provided by the Bernard M. Gordon Center for Systems Engineering at the Technion—Israel Institute of Technology (Grant no. 2011854).

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Res Eng Design (2014) 25:351–373
DOI 10.1007/s00163-014-0182-8

ORIGINAL PAPER

# Steepest-first exploration with learning-based path evaluation: uncovering the design strategy of parameter analysis with C–K theory

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Received: 18 January 2014 / Revised: 16 April 2014 / Accepted: 7 July 2014 / Published online: 18 July 2014


**Abstract** The parameter analysis method of conceptual design is studied in this paper with the help of C–K theory. Each of the fundamental design activities—idea generation, implementation of the idea as hardware and evaluation—is explained and defined as a specific sequence of C–K operators. A case study of designing airborne decelerators is used to demonstrate the modeling of the parameter analysis process in C–K terms. The theory is used to explain how recovery from an initial fixation took place, leading to a breakthrough in the design process. It is shown that the innovative power of parameter analysis is based on C-space "de-partitioning" and that the efficient strategy exhibited by parameter analysis can be interpreted as steepest-first, controlled by an evaluation function of the design path. This logic is explained as generalization of branch-and-bound algorithms by a learning-based, dynamically evolving evaluation function and exploration of a state space that keeps changing during the actual process of designing.

**Keywords** Design theory · Conceptual design · C–K theory · Parameter analysis

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## 1 Introduction

The current study focuses on using C–K theory to clarify the (implicit) theoretical grounds and logic of the pragmatic design method called parameter analysis (PA), and helps explain some notions of C–K design theory. The general logic of the paper is as follows: PA is an intriguing design method based on years of practical application, but the rationale and causes behind it still need clarification. C–K helps build a conceptual model of PA, revealing its inner workings and pointing to future directions of improvement. In this section, we justify the research methodology, provide the background on PA, C–K theory and notions of search and outline the main results.

### 1.1 Methodology: theory-based study of design methods

Studying a specific method with the aid of a theory is common in design research. Reich et al. (2012) analyze ASIT, a derivative of TRIZ, using the C–K design theory, and also elaborate extensively on the validity of studying design methods with theories. They argue that in order to gain deep understanding of a single method and expose in detail the reasons for its performance, a "theory-driven analysis" should be applied. They claim that such theory-based investigations of methods allow furthering our understanding of how and why the methods work, identifying their limitations, areas of applicability and possible improvements, and comparing them to other methods using a common theoretical basis. At the same time, interpreting and demonstrating the methods from the theoretical perspective can provide empirical validation of the theory. Their choice of C–K theory is further explained as follows: "The selection of the theory is rather simple as there is only

one candidate theory that both offers a formal modelling and embeds creativity as an integral part of design, namely the C–K theory."

Other researchers also used C–K theory to explain various design activities, phenomena and methods. For example, Eris (2006) analyzed the pedagogical use of student portfolios with two conceptual frameworks: C–K theory and divergent–convergent inquiry-based design thinking (DCIDT). Elmquist and Segrestin (2007) applied C–K theory to study methods used at the early stages of designing in the pharmaceutical industry. Gillier et al. (2010) investigated the application of a new project portfolio management method using C–K theory. Le Masson and Weil (2013) analyzed the German systematic design methods from a historical perspective with C–K theory, and Shai et al. (2013) conducted a similar study of the Infused Design method (Shai and Reich 2004a, b).

PA is a method to design innovative products (Kroll 2013). Contrary to systematic design methods that prescribe exhaustive listing of functions and their technological solution alternatives (Tomiyama et al. 2009; Smith et al. 2012), PA dictates focusing on the most critical "conceptual design issues" at any given time. And although the success of this logic has been demonstrated empirically (Kroll et al. 2001), there is still no clear theoretical explanation for it. Conventional intuition leads to designing by either extensively reviewing all the pertinent issues in order to avoid late discovery of fatal errors—this is the logic of systematic design, which is robust but time consuming and not completely adapted to certain design situations (Kroll 2013), or relying on a trial and error process—which is also time consuming and risky, unless the designer is very experienced and creative (Pahl et al. 1999). In contrast, PA emerges as a method that is neither a comprehensive overview nor a random walk. Therefore, we ask: what can explain the success of PA? One could attribute it to the experience of designers using PA, but the accumulated evidence (including the one reported here) shows that PA actually helps novice, inexperienced designers to find the way in complex situations requiring some extent of creativity. So the need to investigate the rationale behind PA still remains.

Casting PA in the C–K framework will help to uncover interesting facets of PA. In particular, we show that PA extends the search strategies used to solve complex optimization problems to the domain of design. To this end, the present work also draws upon methods used in artificial intelligence (AI) and operations research (OR), especially those based on branch-and-bound (B&B) algorithms for solving search and planning problems. Brief presentations of PA and some aspects of C–K theory and notions of search that will be useful in this paper follow.

### 1.2 The parameter analysis design method

Parameter analysis (Kroll et al. 2001; Kroll and Koskela 2012; Kroll 2013) is an empirically derived method for doing conceptual design. It was developed initially as a descriptive model after studying designers in action and observing that their thought process involved continuously alternating between conceptual-level issues (concept space) and descriptions of hardware[1] (configuration space). The result of any design process is certainly a member of configuration space, and so are all the elements of the design artifact that appear, and sometimes also disappear, as the design process unfolds. Movement from one point to another in configuration space represents a change in the evolving design's physical description, but requires conceptual reasoning, which is done in concept space. The concept space deals with "parameters," which in this context are functions, ideas and other conceptual-level issues that provide the basis for anything that happens in configuration space. Moving from concept space to configuration space involves a realization of the idea in a particular hardware representation, and moving back, from configuration to concept space, is an abstraction or generalization, because a specific hardware serves to stimulate a new conceptual thought. As will be shown later, concept space in PA is fundamentally different from C-space in C–K theory.

To facilitate the movement between the two spaces, a prescriptive model was conceived, consisting of three distinct steps, as shown in Fig. 1. The first step, parameter identification (PI), consists primarily of the recognition of the most dominant issues at any given moment during the design process. These may include the dominant physics governing a problem, a new insight into critical relationships between some characteristics, an analogy that helps shed new light on the design task or an idea indicating the next best focus of the designer's attention. Parameters play an important role in developing an understanding of the problem and pointing to potential solutions.

The second step is creative synthesis (CS). This part of the process represents the generation of a physical configuration based on the issue recognized within the PI step. Since the process is iterative, it generates many physical realizations, not all of which will be very interesting. However, the configurations allow one to see new key parameters, which will again stimulate a new direction for the process. The third component of PA, the evaluation (E) step, facilitates the process of moving away from a

[1] Hardware descriptions or representations are used as generic terms for the designed artifact; however, nothing in the current work excludes software, services, user experience and similar products of the design process.

physical realization back to parameters or concepts. Evaluation is important because one must consider the degree to which a specific implementation represents a possible solution to the entire problem. Evaluation also uncovers the weaknesses of the configurations and points out possible areas of improvement for the next design cycle. The unique role played by the evaluation function is elaborated later.

PA's repetitive PI–CS–E cycles are preceded by a technology identification (TI) stage of determining the most challenging functional aspect of the task, and looking into fundamental technologies and physical principles that can be used, thus establishing several starting points or initial conditions for PA. A cursory listing of each candidate technology's pros and cons follows, leading the designer to pick the one that seems most likely to succeed. While this may seem to resemble the technique of functional decomposition (or analysis) and morphology, widely used in systematic design (e.g., Pahl et al. 2007), this is not really the case here. In TI, only the most difficult aspect(s) of the overall design task are addressed, as opposed to dealing concurrently with possibly many functions and sub-functions in the morphological approach. Figure 2 is a diagram depicting the place of TI and PA as the means for carrying out conceptual design within the design process. Because the logic of TI is quite similar to what follows in PA, we sometimes refer to their combination as the PA methodology.

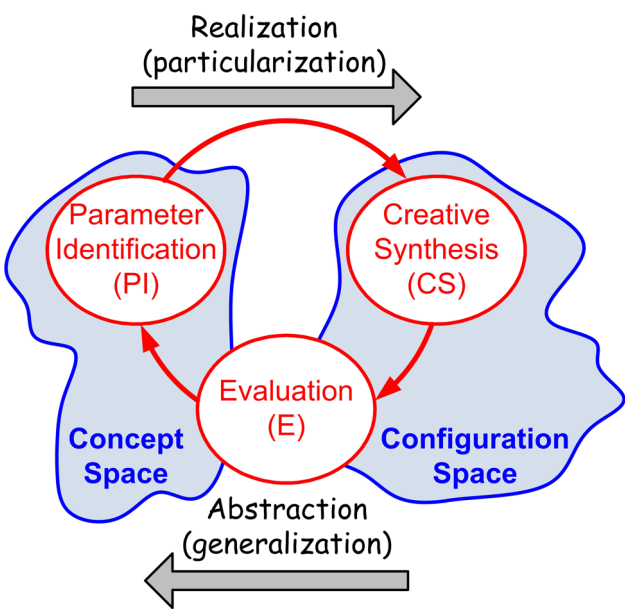



**Fig. 1** The prescriptive model of PA consists of repeatedly applying parameter identification (PI), creative synthesis (CS) and evaluation (E). The descriptive model of moving back and forth between concept space and configuration space is also shown

The TI stage presents yet another enigmatic aspect: On the one hand, it avoids dealing with too many functions and their solution technologies by directing the designer to address only the core of the design task, for the sake of efficiency. On the other hand, we shall see that the method also enables recovery from a misled focus by a form of constructive backtracking: The user can at any point add new solution technologies, even revise the definition of the core task. This kind of recovery and backtracking processes has already been extensively studied in relation to search algorithms (Russell and Norvig 1995), so notions from that field will be used here to provide new insights on the design method.

### 1.3 Analogy to search

Design cannot be treated as a mere search problem (e.g., Hatchuel 2001) because the state space is not known, the goal state is not given, and often even the root state (the task) is ill-defined and evolves together with its solution (Dorst and Cross 2001; Maher and Tang 2003; Wiltschnig et al. 2013). However, search and design problems share a common theme of optimization in a broad sense. Design is not optimization in the "classic" computational problem-solving meaning, but it is concerned with finding good solutions, not just any solution. It also tries to reach the solution in an efficient manner, that is, with minimum resources such as time and knowledge acquisition effort. In order to better understand the observed efficiency of PA, some sort of optimization framework needs to be consulted.

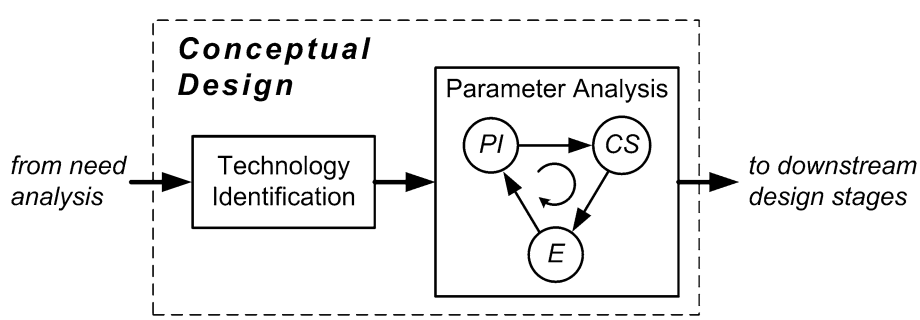



**Fig. 2** Technology identification is the first stage of conceptual design, wherein fundamental solution principles are proposed. It is followed by PA, the process of elaborating the solutions

One of the best known search methods, B&B, is a technique for finding optimal solutions to integer programming problems with a very large number of solutions (e.g., Hillier and Lieberman 2005, chapter 11). The basic idea is to divide and conquer so only a small fraction of the feasible solutions need to be examined. An original large problem is divided (the branching) into smaller and smaller subproblems that are more manageable. The conquering is done by bounding how good the best solution in the subset of feasible solutions can be, and then discarding the subset if its bound indicates that it cannot possibly contain an optimal solution for the original problem. Many algorithms have been developed over the years, employing various search strategies such as breadth-first and depth-first, which differ in the order of expanding the nodes of the search graph to form subsets of the solution space.

Pearl (1984) points to the fact that the emphasis of B&B methods in OR is on the split-and-prune paradigm that is effective in establishing completeness and optimality. In contrast, the AI approach is concerned with the generate-and-test viewpoint, which is more relevant to creating or constructing new objects while searching for solutions. Heuristic[2] search in the context of path-seeking problems has been studied both in OR and AI, with the purpose of increasing efficiency. The most common use of heuristic information has been the bounding functions which control the B&B search, as in AI's popular heuristic shortest-path algorithm called $A^*$ (e.g., Russell and Norvig 1995). These kinds of algorithms might be useful in design since they could help in reducing the number of design alternatives to be explored.

Interestingly, PA appears to be an odd combination of design and search.[3] It is a design process in the sense that there is no target solution at the beginning (contrary to classical "problem solving" cases) and surprises and discoveries are expected at each step, particularly through the evaluation of configurations. But its reasoning process and strategy also share many features with B&B methods: PA incorporates opportunities and activities of diverging that seem similar to B&B's branching, and PA relies heavily on constantly evaluating the artifact, and this is analogous to B&B's bounding by a cost function. Hence, studying PA might help to understanding how B&B can be extended to design processes. To make this extension rigorous, we use a design theory, C–K, to better follow how PA actually helps to navigate strategically in the unknown (unknown state space, unknown goal state), just as B&B helps to traverse the space of a complex optimization problem (with complex but known state space and goal state).

### 1.4 The C–K theory of design

C–K theory (Hatchuel and Weil 2003, 2009; Le Masson et al. 2010) is a general descriptive model with a strong logical foundation (Kazakçi et al. 2008), resulting in powerful expressive capabilities. The theory models design as interplay between two spaces, the space of concepts (C-space) and the space of knowledge (K-space). Four operators allow moving between and within these spaces to facilitate a design process: C → K, K → C, C → C and K → K. Space K contains all established, or true,[4] propositions, which is all the knowledge available to the designer at any given moment during the design process. Space C contains "concepts," which are undecidable propositions (neither true nor false) relative to K, that is, partially unknown objects whose existence is not guaranteed in K. A concept is a hypothesis of the following form: "there exists an entity $x$, for which the attributes $A_1, A_2, \ldots, A_i$ are true in K." Design processes aim to transform undecidable propositions into true ones by jointly expanding spaces C and K through the action of the four operators. This expansion continues until a concept becomes an object that is well defined by a true proposition in K. Expansion of C yields a tree structure, while that of K produces a more richly networked pattern. This short introduction already shows that C–K theory provides a representation of the imaginable "states" in its C-space, and this representation happens to have a tree-shape, just like the structure of the state space in B&B. Moreover, C–K theory tracks in K-space the knowledge expansion, i.e., all the knowledge acquired and used during the design process. In particular, the evaluation criteria of the product to be designed are stored and enriched in K-space. Hence, C–K theory appears to be a powerful framework to interpret the design activities used when designing with PA.

### 1.5 The main results

Using C–K theory and search and graph traversal notions, the present paper draws an analogy between the PA design method and search algorithms to shed light on the reasoning behind the design activities and the overall design strategy of PA. It does not deal with computable cost functions as in OR and AI, but interprets the specific discovery and elaboration process of the design artifact as an extended search process. The paper derives two main results:

[2] 'Heuristic' here means an experience-based technique, rule of thumb, intuitive method, etc.

[3] Connecting design to search, which is the process of exploring a state space, has been studied quite intensively and many techniques are available. An overview can be found in Dym and Brown (2012).

[4] 'True' here does not imply absoluteness; rather, it means that something is considered correct or valid in the designer's mind.

1. The evaluation step built into each cycle of concept development with PA first assesses the evolving design configuration, and this is followed by implicitly assigning "values" to all pending concepts and making a decision as to the next move. Indeed, the original PA method never mentioned value assignment; the clarification of this implicit activity is an original contribution of this paper. The values are assigned subjectively, based on the designer's judgment. Many decisions in design are subjective, and the PA method only provides the framework to make those decisions. A positive (high value) evaluation result will guide the development further down along the same path, while a negative evaluation will direct the process to another, more appropriate path or branch of the concept tree. *PA can therefore be regarded as a generalized B&B process*, guided by evaluation but with two main extensions: The evaluation function in PA evolves over time because it is *subject to learning,* and the "branching" that takes place in PA is actually a design step, since the parameters and configurations are not chosen from a closed list but rather *result from this learning*. In fact, branching can even take place to a new path, previously unknown, that is discovered and generated while designing.
2. The logic of PA provides *strategic guidance in the concept tree of C-space* toward the goal. We show that it can be characterized as a depth-first strategy, which is known in AI to provide quick results, and we show that this strategy is efficient, in the sense that it enables to minimize the exploration needed to reach an acceptable design. At the same time, *it allows backtracking to a higher level if necessary*, which corresponds to a C–K theory "de-partition" or "inclusion," and thus supports innovation. Moreover, the depth-wise exploration is controlled by the PI steps in what we call "steepest-first" manner, that is, addressing the more difficult and challenging issues first. These critical parameters, in PA terminology, are not fixed during the design process; rather, they keep changing.

### 1.6 Summary

To establish these results, a rigorous interpretation of each PA step in C–K terms had to be developed first. The exact meaning of the elements of C-space and K-space, the nature of the four operators and a consistent way of drawing C–K diagrams were all established. The structure of the paper is therefore as follows: The PA method is demonstrated in the next section by applying it to a conceptual design task and explaining the pertinent activities. Next, the PA steps are modeled with the spaces and operators of C–K theory based on the logic and reasoning of both the design method and the theory. This is followed by a step-by-step demonstration of the case study in C–K terms. The paper concludes with a discussion of the results of this study and their consequences in regard to both PA and C–K theory.

It should be noted that although a design method (PA) and a design theory (C–K) are used in this paper extensively, there are still activities and phenomena that are not covered by either of them. Design is a complex human cognitive activity that no single model can fully explain, nor can it be completely encompassed by computer algorithms such as B&B. The methods and theories of design can guide designers, but the quality of the designers' knowledge and decisions still plays an important role in the success of the process. The subjectivity of the decisions and their limitations as related to the notion of "bounded rationality" (Simon 1972; Kahneman 2003) cannot be avoided and should not be regarded as a deficiency, but rather as an inseparable aspect of real design practice.

## 2 Parameter analysis case study

The following is a real design task that had originated in industry and was later changed slightly for confidentiality reasons. It was assigned to teams of students (3–4 members in each) in mechanical and aerospace engineering design classes, who were directed to use PA for its solution after receiving about 6 h of instruction and demonstration of the method. The design process presented here is based on one third-year mechanical engineering team's written report. This was a semester-long project that started with identifying and analyzing the need, and ended with detail design. Only part of the students' conceptual design process is used here.

The task was to design the means of deploying a large number ($\sim$500) of airborne sensors for monitoring air quality and composition, wind velocities, atmospheric pressure variations and so on. The sensors were to be released at altitudes of some 3,000 m from an under-wing container carried by a light aircraft and stay as long as possible in the air, with the descent rate not exceeding 3 m/s (corresponding to the sensor staying airborne for over 15 min). Each sensor contained a small battery, electronic circuitry and radio transmitter, and was packaged as a $\phi$10 by 50-mm long cylinder weighing 10 g. It was necessary to design the aerodynamic decelerators to be attached to the payload (the sensors), and the method of their deployment from a minimum weight and size container. The following focuses on the decelerator design only.

The design team began with analyzing the need, carrying out some preliminary calculations that showed that at the relevant Reynolds number, the drag coefficient $C_D$ of a

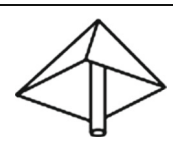
| ***Parameter Analysis Terminology*** | ***Reasoning Process*** | ***Outcome*** |
|---|---|---|
| Design task statement | None (the "brief" is provided by the customer) | Design the decelerators for the given sensors and their means of packing and deployment in the air. |
| Need Analysis | Not described here. Can be done in several ways, such as QFD. It turns the "brief" into design requirements (specs.) | Design requirements:<br>Sensors + low-cost decelerators packed compactly in container and staying in the air for 15 minutes, … |
| Technology Identification (TI) | What's the most difficult aspect of the task? | Deceleration of the sensors (and not packing, deployment, etc.). |
| | Which physical principles or technologies can be used to produce the deceleration? | Aerodynamic drag and buoyancy with the following technologies:<br>1. Flexible parachute<br>2. Rigid parachute<br>3. Balloon filled with light gas<br>4. Balloon filled with hot air. |
| | What's the behavior of each technology? Which is the best candidate? Pros and cons of each are listed and reviewed. | Flexible parachutes are most common in similar applications; rigid parachutes seem difficult to pack compactly; balloons may be much more complicated (inflation or heating needed). Hence, the technology of producing a large drag force by a flexible parachute seems most promising. |
| $PI_1$ | The first conceptual issue (parameter) should be the chosen technology. | Parameter: "Produce a large enough drag force using a flexible parachute". |
| $CS_1$ | Which particular physical structure would realize the flexible parachute concept? | Configuration: A 150-mm dia. hemispherical parachute, connected to the sensor with cords.  |
| $E_1$ | What's the behavior of the hemispherical flexible parachute? | Drag force is ok and compact packing can be done by folding, but the parachute may not open because there isn't enough "pull" on it, and the cords may tangle. |
| | Shall we try to improve the last configuration or backtrack? | Try another technology from the TI stage. |
| $PI_2$ | Use the next best technology for the decelerator design. | Parameter: "Use a rigid parachute to generate drag force". |
| $CS_2$ | Which particular physical structure would realize the rigid parachute concept? | Configuration: A 150-mm diagonal square pyramid with the sensor rigidly attached.  |
| $E_2$ | What's the behavior of the pyramidal rigid parachute? | Drag force is ok but compact packing is impossible because these configurations cannot nest inside each other. |
| | Shall we try to improve the last configuration or backtrack? | Try to improve the design by finding a way to pack it compactly. |

**Fig. 3** Description of the PA process used to design the airborne decelerators based on one team's written design report. The original presentation has been modified for brevity and clarity, but the content is preserved (continued on next page)

parachute-shaped decelerator is about 2, so to balance a total weight of 12–15 g (10 g sensor plus 2–5 g assumed for the decelerator itself), the parachute's diameter would be $\sim$150 mm. If the decelerator is a flat disk perpendicular to the flow, the $C_D$ reduces to $\sim$1.2, and if it is a sphere, then $C_D \cong 0.5$, with the corresponding diameters being

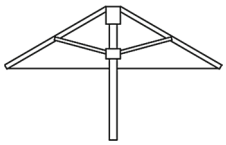
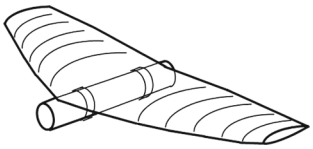
| | | |
|---|---|---|
| $PI_3$ | How can the last configuration be improved? Combine the idea of flexible parachute that can be folded for packing with a rigid parachute that doesn't have cords and doesn't require a strong "pull" to open. | Parameter: "Use a frame + flexible sheet construction that can fold like an umbrella; use a spring for opening" |
| $CS_3$ | Which particular physical structure would realize the "umbrella" concept? | Configuration: Lightweight skeleton made of plastic or composite with "Saran wrap" stretched and glued onto it. Hinges and slides allow folding. A spring will facilitate opening.  |
| $E_3$ | What's the behavior of the "umbrella" parachute? | Drag force and compact packing are ok, but this structure is unreliable and expensive to manufacture because of the many moving parts. |
| | Shall we try to improve the last configuration or backtrack? | Parachutes (flexible and rigid) are problematic. Abandon this concept and try something else. |
| $PI_4$ | Let's look at the problem differently, from an energy dissipation viewpoint instead of producing retarding force. Dissipation of the sensor's initial potential energy can be carried out by a long enough distance over which a smaller drag force can act. | Parameter: "Use a small aircraft that glides in spirals". |
| $CS_4$ | Which particular physical structure would realize the glider concept? | Configuration: Wings with a span of 200 mm and a small twist to produce a 30-m diameter downward spiral. The wings can be made of Styrofoam and the sensor attached with plastic clips.  |
| $E_4$ | What's the behavior of the spiraling glider? | This would work, seems cheap to make, and shouldn't have deployment problems. But how will the "gliders" be packed and released in the air? |
| | Shall we try to improve the last configuration or backtrack? | Continue with this configuration: design the container, packing arrangement, and method of deployment. |

**Fig. 3** continued

about 200 and 300 mm, respectively. It was also clear that such large decelerators would be difficult to pack compactly in large numbers, that they should be strong enough to sustain aerodynamic loads, particularly during their deployment, when the relative velocity between them and the surrounding air is high, and that being disposable, they should be relatively cheap to make and assemble. Further, the sturdier the decelerator is made, chances are that it will also be heavier. And the heavier it is, the larger it will have to be in order to provide enough area to generate the required drag force.

Figure 3 is a detailed description of the TI stage followed by the first portion of the PA process carried out by the design team. The distinct reasoning steps are listed alongside their respective outcomes. The wording and illustrations have been slightly modified for better clarity, but in essence, they follow the original students' work, which was a written report consisting of describing the TI stage as an essay and then listing of each PA step explicitly.

TI begins with the team specifying deceleration of the sensors as the most critical aspect of the design. For this

task, they come up with the technologies of flexible parachute, rigid parachute, gas-filled balloon and hot-air balloon. Flexible parachutes can easily be folded for compact packing and represent a very common technological solution for slowing down the descent of airborne objects. Rigid parachutes can be made in various shapes, e.g., pyramids, cones or flat surfaces, and are also used in some similar applications. The balloons use both buoyancy and aerodynamic drag and can be packed compactly when deflated, but inflating or heating during or after deployment seems difficult. The concept chosen by the designers for further development is therefore the flexible parachute.

The first parameter identification step ($PI_1$) according to the PA method is simply to use the chosen technology as starting point. The concept ("parameter") is therefore to have a small conventional parachute provide the necessary drag force and allow compact packing in its folded state. The subsequent creative synthesis step ($CS_1$) realizes this idea in a specific hardware by sketching the configuration and sizing it with the help of some drag force calculations. Having a configuration at hand, evaluation can now take place ($E_1$), raising doubts about the operability of the solution: The 10-g weight of the payload may not exert a strong enough "pull" to open the parachute, and the cords may tangle during opening. Still within the evaluation step, the designers decide to abandon the flexible parachute concept and try another technology.

The next concept attempted ($PI_2$) is the rigid parachute from the TI stage, implemented as a square pyramid configuration ($CS_2$), but found to introduce a new problem—packing—when evaluated ($E_2$). Deciding to pursue this concept further, the designers propose a folding, semirigid parachute as the next concept ($PI_3$). It is implemented as an "umbrella" (a folding rigid skeleton with flexible canopy, $CS_3$) and evaluated ($E_3$), resulting in the conclusion that parachutes are not a good solution direction. This brings about a breakthrough in the design: Instead of thinking about producing a large retarding force to act over the vertical height of 3,000 m, which resulted in large structures that were unreliable and expensive, perhaps the problem should be considered from an energy viewpoint. Decelerating a falling object is concerned with dissipating potential energy by frictional work, and this can also be achieved by a smaller drag force over a larger distance, so instead of a vertical fall, the payload can be carried by a "glider" in a spiraling descent ($PI_4$). The resulting configuration ($CS_4$) shows an implementation of the last concept in words and a sketch, to be followed by an evaluation ($E_4$) and further development.

Several interesting points in this process are noteworthy. First, when the designers carried out preliminary calculations during the need analysis stage, they already had a vertical drag device in mind, exhibiting the sort of fixation in which a seemingly simple problem elicits the most straightforward solution. Second, TI yielded four concepts, all still relevant for vertical descent, and all quite "standard." A third point is that while the designers focused on synthesizing a device to slow down the descent, they constantly kept in mind the other required functionalities, such as compact packing, low cost and high reliability, as can be seen in the evaluation steps. Finally, it is interesting to note that when the "umbrella" concept failed ($E_3$), the designers chose not to attempt another technology identified at the outset (such as gas-filled balloon), but instead used the insights and understanding gained during the earlier steps to arrive at a totally new concept, that of a "glider" ($PI_4$). And while in hindsight this last concept may not seem that innovative, it actually represents a breakthrough in the design process because this concept was not apparent at all at the beginning.

We can conclude that PA seems to have allowed and supported a complex design process leading to a breakthrough when the known solutions were not sufficient and innovative alternatives became unavoidable. PA exhibited an interesting feature of recovery from a dead-end caused by a misled initial focus, and this recovery seems to have followed a form of constructive backtracking in the sense that the designers retreated from their initial focus but still kept in mind what had been learned during the initial exploration. This recovery and constructive backtracking can eventually lead to a breakthrough. Of course, this process depends on the designer's knowledge, experience and ability to use the method; however, it is interesting to clarify what in the method helps reach this "necessary breakthrough." To answer this, we need to interpret PA in terms of C–K theory.

## 3 Interpretation of parameter analysis activities in terms of C–K theory

Each of PA's reasoning steps described in the previous sections is broken down to elementary "moves" in order to formulate them as sequences of C–K operators. The basic premise for doing so is the epistemological difference in the meaning of "concept" between PA and C–K. Because knowledge is not represented explicitly in PA and because a design should be considered tentative (undecidable in C–K terms) until it is complete, both PA's parameters and configurations (i.e., the members of PA's concept space and configuration space, respectively) are entities of C–K's C-space. In other words, C–K theory does not distinguish between a concept's ideological foundation and its structural aspects while PA does. However, this is not meant to imply that no knowledge is used in PA's reasoning process; on the contrary, existing knowledge is extensively utilized

in each PA step and new knowledge is constantly generated, so excursions to K-space should be incorporated in the interpretation.

### 3.1 Technology identification

Technology identification (TI) is a separate stage in the PA methodology that is done first. It involves three distinct reasoning steps:

1. *What is the most difficult aspect of the design task?* Here, the designer decomposes the overall task into sub-tasks and uses his/her knowledge and judgment to identify those sub-tasks that are relatively easy or have known solutions, and those that seem the most challenging, whose solution direction is not straightforward, or those requiring innovative approaches. Usually, only one or two such difficult tasks will be identified.
2. *Which physical principles or core technologies could be used to satisfy the difficult sub-task(s)?* Here the designer uses knowledge in the problem domain or looks externally (Internet, expert consultation, etc.) for similar problems and solutions. If none is found, or if some configurative solution is identified, the designer should abstract and generalize the sub-task at hand to the level of fundamental technological or physical principles.
3. *What is the behavior of each technology in the context of the task?* Cursory listing (and not a thorough selection process) of the pros and cons of each technology. Which one is the most promising candidate? It is implied here that some evaluation criteria can be found, perhaps among the design requirements, and that their application is analogous to assigning a "value" to each technology. A higher value implies that according to the designer's judgment, the technology has better chances of resulting in a successful solution.

Interpreting these steps in C–K terms is shown in Fig. 4, with numbers attached to the arrows to denote the order of operations. K-space consists of existing knowledge items, marked by white background, and new knowledge that is shown with dark background. It begins with the known description of the overall design task (the "brief") and the design requirements generated earlier. First, a K → K operator describes the isolation of the most difficult functional aspect of the task (step 1 above), followed by a K → C operator to establish the root concept, $C_0$. Core technologies for the main function are next generated by the designer based on existing knowledge and similar applications. This step (2 above) requires returning to K-space (a C → K operator), listing the possible

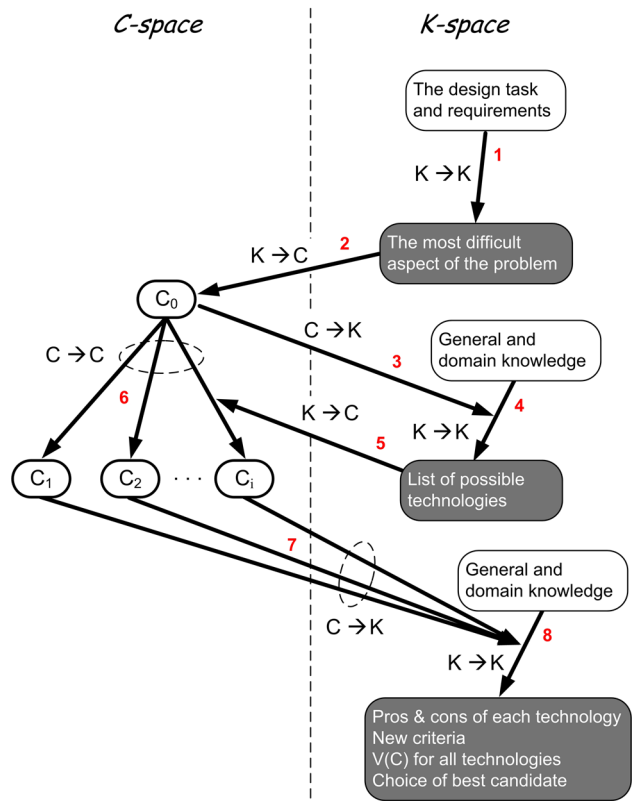



**Fig. 4** Modeling the technology identification (TI) stage in C–K theory terms. The root concept $C_0$ is established, possible technologies identified and evaluated, yielding a value V($C$) for all concepts. Finally, the best candidate is selected for further development

technologies (K → K), and moving to C-space (K → C) to trigger the expansion of $C_0$ into $C_1$, $C_2$,…, $C_i$, which are concepts based on those technologies (a C → C operation). Finally, step 3 above calls for evaluating the candidate concepts and choosing among them. This is accomplished with a C → K operator that activates knowledge in K-space (K → K) to arrive at the desired outcome. A more rigorous explanation of how evaluation and selection work by assigning and maximizing a value is presented later in this section and in Sect. 4.

One point that may need clarification regarding this model is how the identified technologies can reside in both K-space and C-space at the same time. The answer lies in the different meaning (and therefore, logical status) of each occurrence: In K-space, the meaning is of technologies that are more or less known to be used in similar applications, and thus, they constitute knowledge items in the designer's mind; in C-space, the meaning is of undecidable propositions, suggesting using these technologies to accomplish the specific task $C_0$. Note also that formally speaking, whenever a node of the concept tree in C-space is expanded (a "partition" in C–K terms), there is at least one more edge or path with the meaning of "other" that is not shown because it has not been explicitly used by the designer.

### 3.2 Parameters and configurations as attributes of C–K concepts

Following TI, the actual PA process consists of three steps (PI, CS and E) that are applied repeatedly and involves two types of fundamental entities: parameters (ideas, conceptual-level issues) and configurations (hardware representations, structure descriptions). To accommodate both entities in the C–K theory model, a refinement of the definition of a C–K concept as given in Sect. 1 is needed to distinguish between attributes that convey functional and behavioral purpose and meaning, and those that describe physical features. The former attributes are added at the PI step and correspond to PA's parameters. We shall call them "ideational" to emphasize that they contain the ideas that will eventually have led to the solution and denote them by $P_1$, $P_2$, etc. The latter attributes, on the other hand, are added at the CS step and correspond to PA's configuration items. We shall call them "structural" because they contain descriptions of hardware (see Footnote 2) and denote them as $S_1$, $S_2$, etc. That both types of attributes play a role in elaborating the design and therefore in describing a C–K concept, is a fundamental notion of PA that is also in line with Roozenburg's (1993) combinations of *mode-of-action* and *form* and Weber's (2005) combinations of (behavioral) *properties* and (structural) *characteristics*. The modified form of a C–K concept can now be written as "there is an object $C_i$, for which the ideational attributes $P_1, P_2,\ldots, P_m$ obtained with the structural attributes $S_1, S_2,\ldots, S_n$ are true in K." For brevity, we may also describe a concept as $C_i$ ($P_1$, $P_2,\ldots$, $P_m$, $S_1$, $S_2,\ldots$, $S_n$), preserving the original meaning.

Ideational and structural attributes differ not only in their meaning, but also in their role in the design process. Ideational attributes are used to define the evolving concept and represent the deep reasoning, the "ideology," behind the solution. They are explicitly integrated into the concept description in the PI steps as the "design path" and strongly and directly controlled during the design process by the results of the evaluation step. Structural attributes, on the other hand, are needed mainly to facilitate the evaluation and are more temporal in nature: They keep changing while developing the concept and may even be revised later, after completing the conceptual design phase and doing embodiment and detail design. In this sense, the structural attributes are not as significant as the ideational ones and only weakly and indirectly controlled through the CS steps; in other words, a change in the configuration is possible only by means of an ideational step (PI) and those changes usually are not unique.

### 3.3 The creative synthesis step

Having established the nature of a C–K concept's attributes, it is now possible to elaborate each of PA's reasoning steps. The outcome of the design process is clearly a member of PA's configuration space, so the interpretation begins with the CS step being applied to a PA parameter and results in a new configuration. CS involves a realization of an idea in hardware representation by particularization or instantiation (the opposite of generalization). It usually requires some quantitative specification of dimensions, materials, etc., that are derived by calculation, but not more than is required to establish the behavior of the configuration. In terms of C–K theory, if PA's parameters and configurations are both elements of C-space, then the CS step should start and end in C-space. However, because knowledge is required to realize an idea in hardware and perform quantitative reasoning, a visit to K-space is also needed. The CS step therefore begins with a C → K operator for searching for the needed knowledge by triggering a K → K (deriving specific results from existing knowledge). The new results, in turn, are used by a K → C operator to activate a C → C that generates the new concept, which adds structural attributes to realize the latest ideational attribute. This interpretation of CS as a sequence of four C–K operators is depicted in Fig. 5, where $C_{i+1} = C_i + S_{n+1}$. C–K concepts generated by adding PA parameters (C–K ideational attributes) are denoted in the figures by round-cornered boxes, while those resulting from adding PA configurational elements (C–K structural attributes) are shown as regular boxes. C–K's root concept, $C_0$, does not have structural attributes, so it will always have rounded corners, as in Fig. 4.

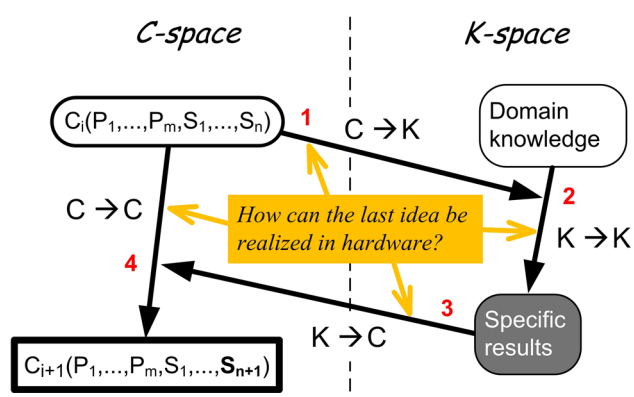



**Fig. 5** Modeling the creative synthesis (CS) step in C–K theory terms. The latest ideational attribute $P_m$ of concept $C_i$ (which corresponds to a PA parameter) is implemented as structural attribute $S_{n+1}$ of concept $C_{i+1}$

### 3.4 The evaluation step

One of the basic premises of PA is that parameters (concepts, ideas) cannot be directly evaluated in an effective manner; rather, they need to be implemented as configurations first and only then evaluated. This means that the evaluation (E) step begins with a C–K concept that includes structural attributes and attempts to deduce its specific behavior ("given structure, find behavior"), from which it will make a decision as to how to proceed. Reasoning from behavior to decision, however, includes two intermediary steps that are the key to understanding how the evaluation controls the design process so that it always moves in the most promising direction. First, the specific behavior of the configuration is used to establish possible new evaluation criteria, and those are applied (together with existing, older criteria) to all pending concepts to assign a value to them. Finally, a decision is made to move in the direction that maximizes this value.

The C–K interpretation is shown in Fig. 6: A C → K operator is used to initiate a K → K; the former being the operation of looking for the knowledge necessary for the evaluation, while the latter is the deductive reasoning that leads to deriving the specific behavior, new criteria and concept values, and making the decision as to how to proceed. The identification of new evaluation criteria is the actual *learning* done during the design process and is facilitated by having configurations to be evaluated. The combination of CS and E steps allows discovering unexpected behavioral aspects or revealing that some known functional issues have become more critical. New and critical issues in PA form the basis for the following PI step, as explained below.

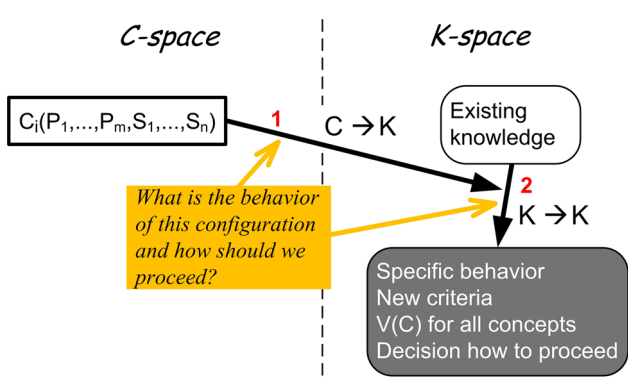



**Fig. 6** Modeling the evaluation (E) step in C–K theory terms. Concept $C_i$ corresponds to a PA configuration and existing knowledge is used to derive its behavior, deduce new evaluation criteria, calculate values V($C$) for all pending concepts including $C_i$ and make the decision as to how to proceed. The new criteria represent learning during design

The E step can be further described as activation of an evaluation function whose input arguments are the current concept $C_i$ and all existing knowledge in K, including evaluation criteria learned in previous E steps. The function returns four arguments: First, the designer examines the configuration of $C_i$ (its structural attributes $S_1,\ldots, S_n$) to see whether it works as it should, if it seems capable of satisfying the requirements, and if anything is still missing; this is the concept's specific behavior. Next, new evaluation criteria may be deduced from the behavior and added to the existing ones, to form a new set of criteria and a new ordering by importance within the set. Thirdly, all the concepts in the current C-space are evaluated with the updated criteria, and "values" V($C$) are assigned to each concept. The values are not numerical, as B&B's costs, but rather a metric that represents the designer's judgment of the goodness and viability of the concept, its potential to lead to a conjunction for $C_0$, even its chances to materialize within given constraints of time and resources. Finally, a decision is made regarding the next move as one of the followings:

(1) *Termination* If the concept's behavior is as desired and nothing is missing (so no new evaluation criteria are added), and the value of the concept is higher than that of any other concept, then the design process is complete. All current attributes of the concept are accepted, and there is no subsequent PI step.
(2) *Following the current path* If an undesired behavior is detected, or something is missing in the concept, but its value is still the highest, then it should be improved by keeping its current attributes and adding a new ideational attribute in the next PI step (this is the most common occurrence).
(3) *Backtracking to a known but unexplored path* If the undesired behavior renders another existing concept more valuable, then the current development path should be stopped, and the next PI step will continue with the new highest value concept.
(4) *Backtracking to an unknown path* If the value of all existing concepts and technologies is very low, then all their attributes should be rejected and backtracking to $C_0$ will take place. The subsequent PI step will attempt to discover a new path.

### 3.5 The parameter identification step

The PI step begins with the results of the evaluation step in K-space, so it is a K → C operator that activates a C → C operator. The K → C operator carries the decision plus specific domain knowledge into C-space, while the C → C operator performs the actual derivation of the new concept.

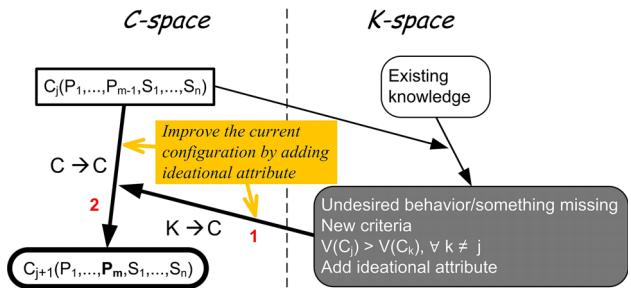



**Fig. 7** Modeling the common occurrence of the parameter identification (PI) step in C–K theory terms following case (2) of evaluation (following the current path). Concept $C_j$ has been evaluated (*thin arrows*) and weaknesses found. New criteria may be generated accordingly, but the value of $C_j$ is still the highest, so ideational attribute $P_m$ is added to form a new concept $C_{j+1}$

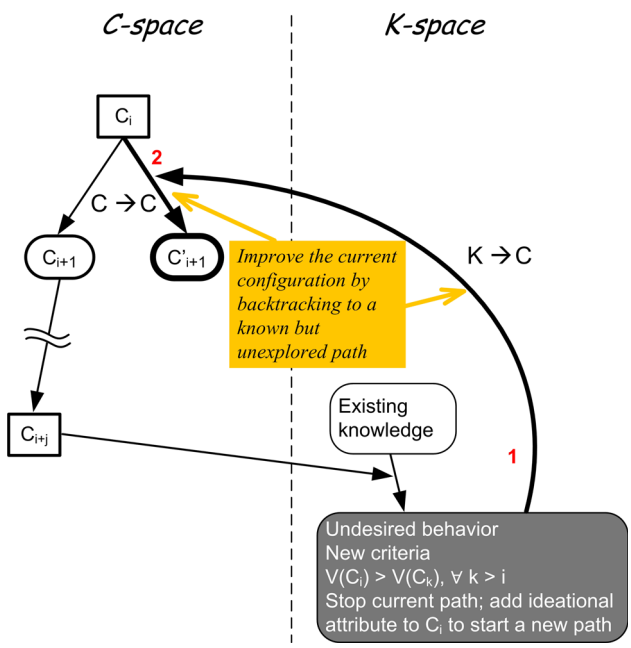



**Fig. 8** Modeling the parameter identification (PI) step in C–K theory terms following case (3) of evaluation (backtracking to a known but unexplored path), with backtracking to a previous concept whose value suddenly becomes the highest. An ideational attribute $P'_m$ is added to $C_i$ and creates a path to $C'_{i+1}$, replacing the attribute $P_m$ in $C_{i+1}$. If $C_i = C_0$ then $C'_{i+1}$ represents a different technology from the TI stage that was known but not used so far

Several cases can be distinguished based on evaluation results (2) to (4) above. The PI step can begin with a decision to improve the current design—case (2) above—as in Fig. 7, by adding an ideational attribute and staying on the current path. The PI step that follows case (3) above (backtracking to a known but unexplored path) is shown in Fig. 8, where a possibly long sequence of developing the concept along a path $C_i$, $C_{i+1}$,…, $C_{i+j}$ has already taken place. However, evaluating $C_{i+j}$ reveals that a previous

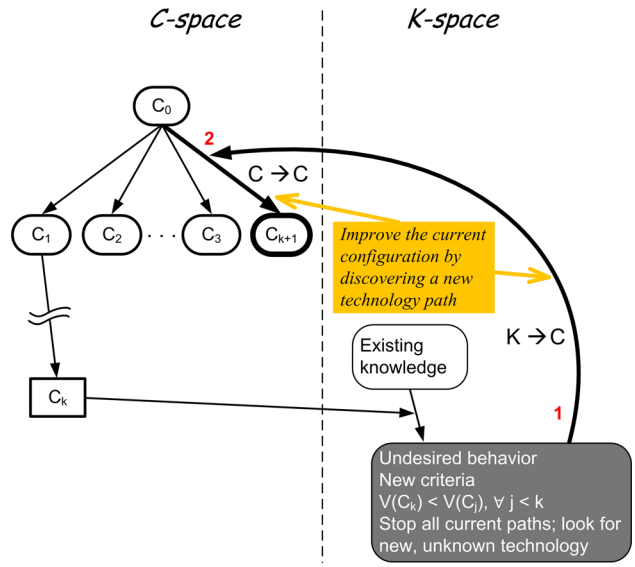



**Fig. 9** Modeling the parameter identification (PI) step in C–K theory terms following case (4) of evaluation (backtracking to an unknown path), with backtracking to the root concept in order to *discover* a new technology. This implies discarding all the previous attributes and starting over

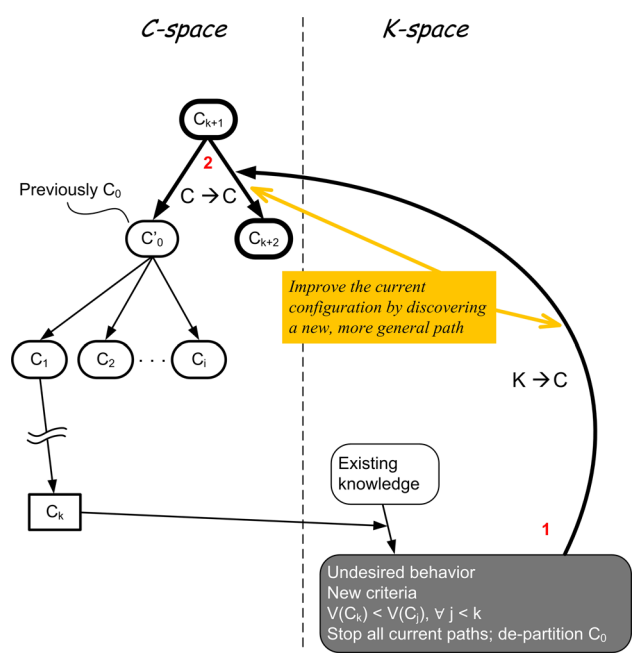



**Fig. 10** Modeling the parameter identification (PI) step in C–K theory terms following case (4) of evaluation (backtracking to an unknown path), with backtracking to *higher* than the root concept in order to revise its identity. $C_{k+1}$ becomes the new, more general root concept; $C'_0$ is a revised version of the previous root concept $C_0$; $C_{k+2}$ is the beginning of a new, perhaps surprising path

concept, $C_i$, now has a higher value, perhaps because the evaluation criteria have changed. Therefore, the current path is not continued, and a new path is developed from $C_i$

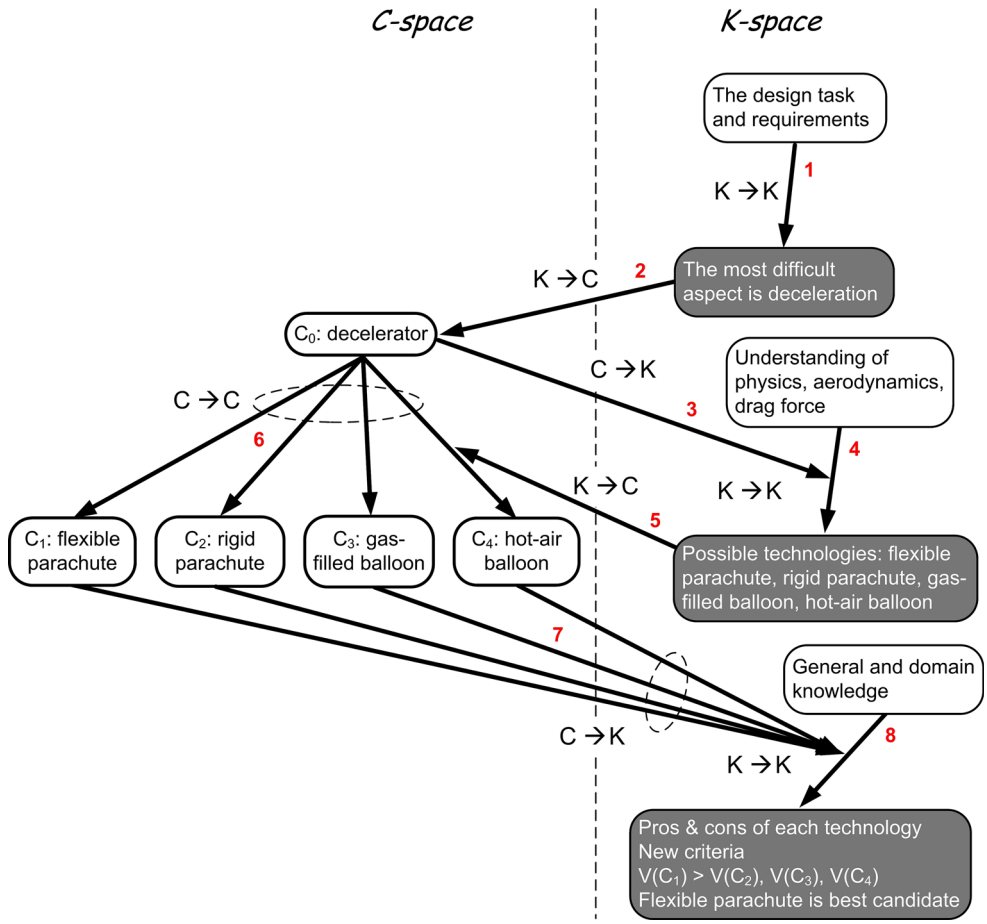



**Fig. 11** C–K modeling of the technology identification (TI) stage of the decelerator design example. Producing drag force, simplicity and compact packing are used as evaluation criteria to assign the highest value to $C_1$, thus initiating a design path based on flexible parachute

instead. The latter path is not entirely new because it is the implicit "other" path that was known to exist when $C_{i+1}$ was derived from $C_i$, but now it is made explicit. An ideational attribute $P_m$ in $C_{i+1}$ will be replaced by $P'_m$ in $C'_{i+1}$. Sometimes, the backtracking required, as revealed by the evaluation, may be so substantial that it forces returning to the root concept and choosing another technology from those generated in the TI stage.

Case (4) of the evaluation step described above (backtracking to an unknown path) can be followed by any of the two possibilities described in Figs. 9 and 10. The designer may feel that the initial set of technologies identified earlier is not good enough, and look for new ones. He or she has by now gained some experience in working on the design task, including learning in K, so a new suitable technology, not considered earlier, may be discovered. This means that the concept development with PA will start over, and the ideational attribute added by the PI step is the technology to use in the new path (Fig. 9).

Finally, it may also happen that the learning during evaluation and the low values assigned to all existing concepts in case (4) of the evaluation ((backtracking to an unknown path) will lead the designer to re-examine the validity of the root concept itself. As shown in Fig. 10, this means that a C–K de-partition takes place, where a new, more general root concept emerges. The previously developed tree in C becomes one branch, while a totally new design path is created as another branch. The phenomenon of de-partition, or growing of the tree structure in C-space upward, at its root, has been demonstrated in (Le Masson et al. 2010, chapter 11).

## 4 Parameter analysis case study interpretation in C–K terms

A C–K-theoretical model of the decelerator design case study of Sect. 2 will now be elaborated to illustrate the results of the previous section. The design process began with the need, the problem to solve, as stated by the customer. A need analysis stage produced greater understanding of the task and the design requirements. This took place entirely in K-space and is not shown here. Next, TI focused the designers on the issue of deceleration ($C_0$), found possible core technologies, evaluated their pros and cons, and made a choice of the best candidate. As shown in

Fig. 11, this stage generated the root concept and four more concepts in C, thus establishing four possible design paths (note that for brevity, concepts in the diagrams list only the last attribute added to them; all other attributes are inherited from their ancestors and not shown):

$C_1 = C_0 + P_1 =$ decelerator based on (or having the ideational attribute of) flexible parachute,
$C_2 = C_0 + P_2 =$ decelerator based on rigid parachute,
$C_3 = C_0 + P_3 =$ decelerator based on gas-filled balloon,
$C_4 = C_0 + P_4 =$ decelerator based on hot-air balloon.

The evaluation of the four candidates at this stage is quite superficial: The designer imagines a decelerator based on that technology and uses some of the design requirements to judge the potential for success. Having only a general description of the technology in mind, the designers of the decelerators estimated that the two balloon technologies would be complicated, that the rigid parachute would be difficult to pack compactly, and so the common, straightforward solution of flexible parachute was valued highest; that is, $V(C_1) > V(C_2), V(C_3), V(C_4)$. Therefore, the evaluation criteria used were the capability to produce drag force (implicit), inherent simplicity (explicit) and potential for compact packing (explicit).

The following description of the PA process commences at this point. Figure 12 shows the first cycle of PI–CS–E as described in Fig. 3 and depicted with the formalism of Figs. 5, 6, 7, 8, 9 and 10. The result of the TI stage, to use a flexible parachute concept for the decelerator, is shown as the first PI step (for clarity, concepts $C_2$, $C_3$ and $C_4$ from TI are not shown now). This idea is next realized in hardware by a CS step, resulting in concept $C_5$ whose meaning is "a decelerator based on (or having the ideational attribute of) flexible parachute and the structural attribute of a 150-mm diameter hemispherical canopy with cords attached to the sensor." This last concept is evaluated by noting its behavior and generating two new criteria: opening in the air and tangling of the cords. These are added to the existing criteria, but their importance is high (these problems may render the concept useless), resulting in concept $C_2$ (see Fig. 11) becoming the highest valued. This corresponds to case (3) of the evaluation as in Fig. 8, so the decision is to abandon the flexible parachute design path and try the existing rigid parachute technology instead.

The second and third PA cycles are now added, as shown in Fig. 13, starting with the pruning of the flexible parachute branch and initiating a new branch based on the technology of rigid parachute ($PI_2$). This concept is realized as a 150 × 150 mm square pyramid ($CS_2$) and evaluated to discover a problem related to packing (an existing evaluation criterion), followed by a decision to improve this aspect of the design ($E_2$). This evaluation corresponds to case (2) of evaluation, so the process continues as in Fig. 7, with the improvement idea of using a folding frame with flexible skin, an "umbrella" ($PI_3$). This is implemented as a structure with rods, hinges, slides, "Saran wrap" and a spring ($CS_3$). Evaluation ($E_3$) of this last configuration produces its specific behavior as being so complicated that it would be costly and unreliable. Simplicity is an existing evaluation criterion used before, and low cost is one of the original requirements, although it is now used explicitly for the first time. Reliability, however, is a new criterion just found. All concepts associated with the rigid parachute technology are now valued low, joining the previously low-rated flexible parachutes. Moreover, the two remaining still untried balloon technologies are also assigned low values now, based on the updated set of criteria (ease of opening in the air and packing compactly, being low cost and reliable). This situation corresponds to case (4) of evaluation, where backtracking to the root concept or higher takes place, as in Figs. 9 and 10.

The fourth PI–CS–E cycle is depicted in Fig. 14. It begins with the evaluation result of step $E_3$ shown at the lower right corner. Having pruned the flexible parachute path earlier, the designers now prune rigid parachutes. They have two choices: either attempt to find a new, previously unknown technology for $C_0$, or revise the identity of $C_0$ by de-partitioning. Their accumulated experience, the learning, from the design process leads them to the understanding that they have so far considered only vertical drag devices and that the still unconsidered balloon technologies also belong to that category. So, they decide to take a fresh look at the problem ($PI_4$ in Fig. 14): From the energy dissipation viewpoint, a spiraling "glider" concept might work better. The C–K model of this step shows a de-partition, representing moving toward a more general concept, and in our case, redefining the identity of $C_0 = decelerator$ to $C_0' = vertical\ drag\ decelerator$ and partitioning $C_9$ to $C_0'$ and $C_{10}$. This last concept is now implemented as the specific configuration $C_{11}$ through the $CS_4$ step and evaluated, resulting in the conclusion that a conjunction for the new root concept has been reached. The design process may now proceed with the secondary issues (as identified in TI) of packing and deployment.

## 5 Discussion

A design theory used to study an empirically derived design method can provide explanation of the activities and phenomena, but also can be supported by the empirical data. The current study's main thrust was shedding light on PA using C–K theory, in particular the "recovery" logic in PA. On the way, some notions related to C–K theory have

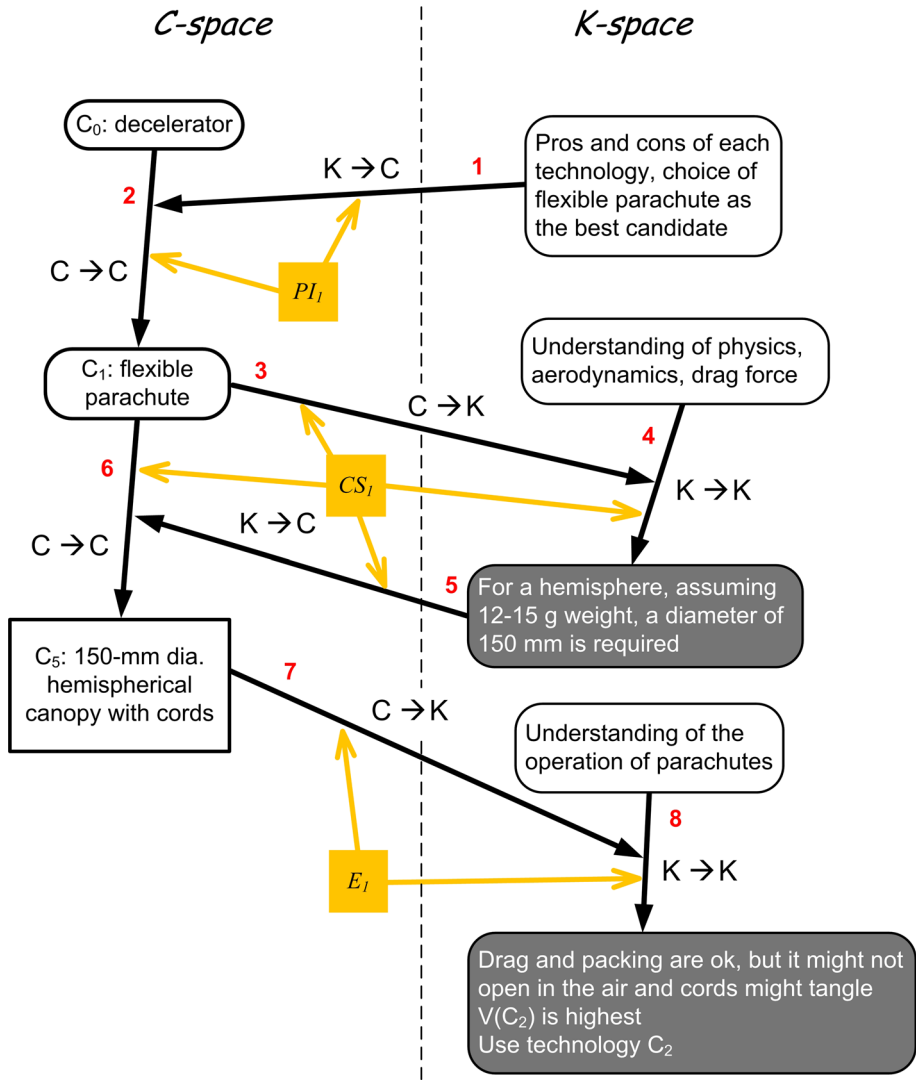



**Fig. 12** C–K modeling of the first PI–CS–E cycle in the decelerator design example. The evaluation criteria are enriched thanks to analyzing the behavior of a configuration, by adding opening in the air and tangling of the cords. This results in the designers assigning the highest value to $C_2$: *rigid parachute* (not shown in the figure)

been clarified. The findings of this work—the interpretation of PA in terms of C–K theory and the inferences regarding the strategy of PA—are based on logical reasoning. The detailed case study is used only for demonstration purposes and is not the source of theoretical conclusions.

The decelerator design example is discussed first, followed by the interpretation of the pertinent entities (the elements of PA and C–K spaces) and design moves (steps and operators, respectively). A design method cannot be based on an "omniscient designer" hypothesis, nor can it be a purely random process; rather, it needs to have a strategy that guides the designer throughout the process. Many design methods appear as iterative processes with concept generation, concept selection and testing, and PA is no exception. Hence, the issue is rather to understand the kind of design strategies that are supported by these methods and that might be more specifically characterized by the methods. The design strategy supported by PA can be portrayed as focusing on one dominant issue at a time, examining known alternatives to address this issue, and, when necessary, looking for a breakthrough. We explain below how these specific features of the PA process can be related to two key aspects of its design strategy, namely the "steepest-first" ordering of the issues to be handled, and the continuous learning-based evaluation of the whole design path during concept development. Together, these aspects account for a certain form of efficiency and innovative capability of the PA methodology.

### 5.1 Recovery and constructive backtracking in the case study

The decelerator case study was chosen for this paper among many examples of using PA for conceptual design because it is relatively easy to follow in terms of the domain knowledge involved, and because it exhibits

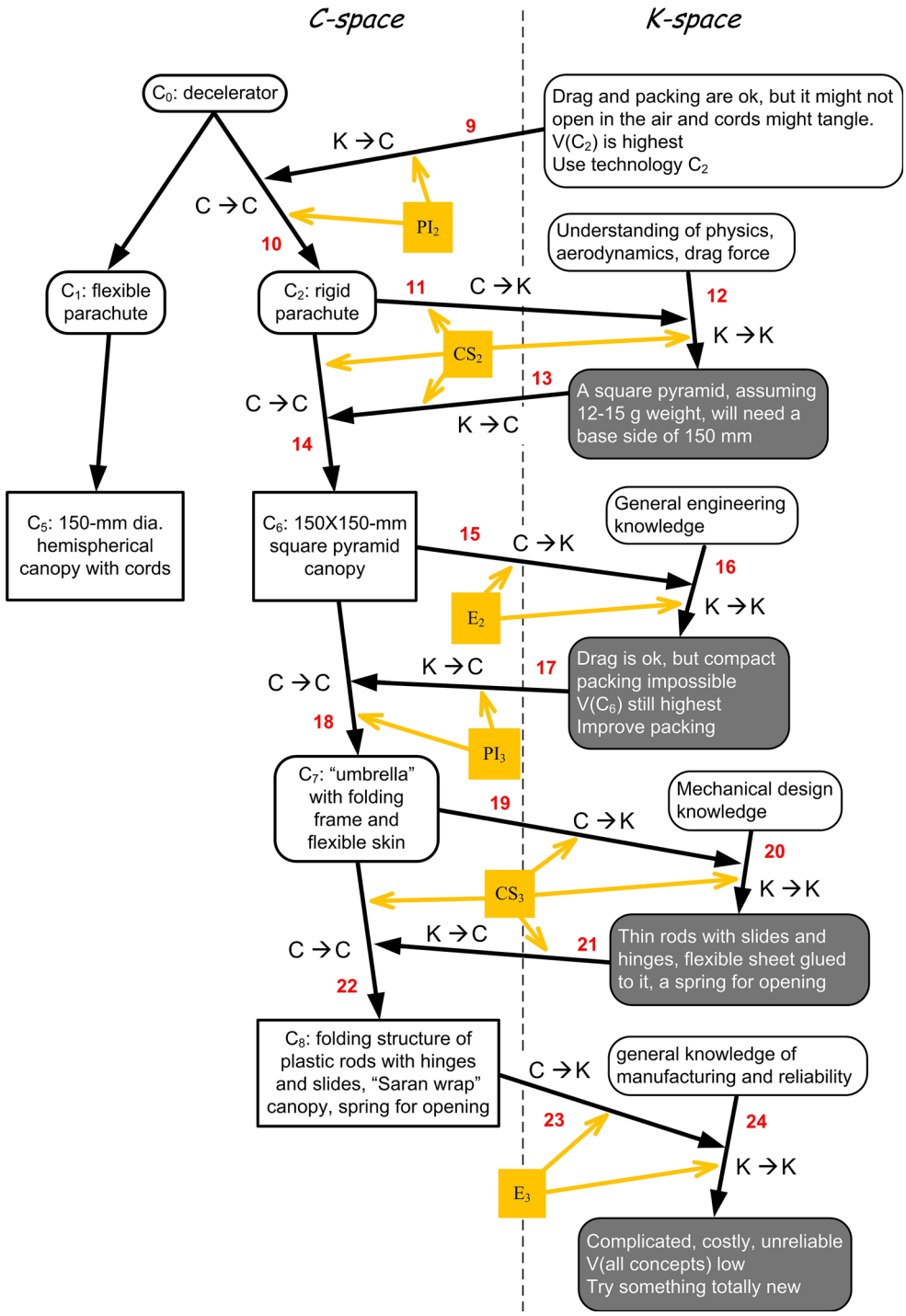



**Fig. 13** The second and third PA cycles are added after pruning the flexible parachute branch. Both attempt to develop a concept with the rigid parachute technology. However, based on an updated set of evaluation criteria, the result is low values for all existing concepts and technologies

several interesting and relevant phenomena in a fairly short sequence of design activities. Other case studies of PA, as in Kroll et al. (2001), Condoor and Kroll (2008) and Kroll (2011), for example, tend to consist of much longer "chains" of PA cycles, sometimes requiring many background explanations to follow. And because the current work offers a rigorous translation of PA moves into C–K operators, a relatively short demonstrating example is just as good as a much more elaborate case study.

At the beginning of the decelerator design process, there was a TI stage of proposing several core technologies, listing their pros and cons, and selecting a best candidate for further development. Next, an attempt was made to pursue that design path, only to abandon it in the face of some difficulties. A complete backtracking took place next, and another design path initiated. This time, problems with the evolving artifact led to trying to improve it, but when more difficulties were encountered, the designers achieved

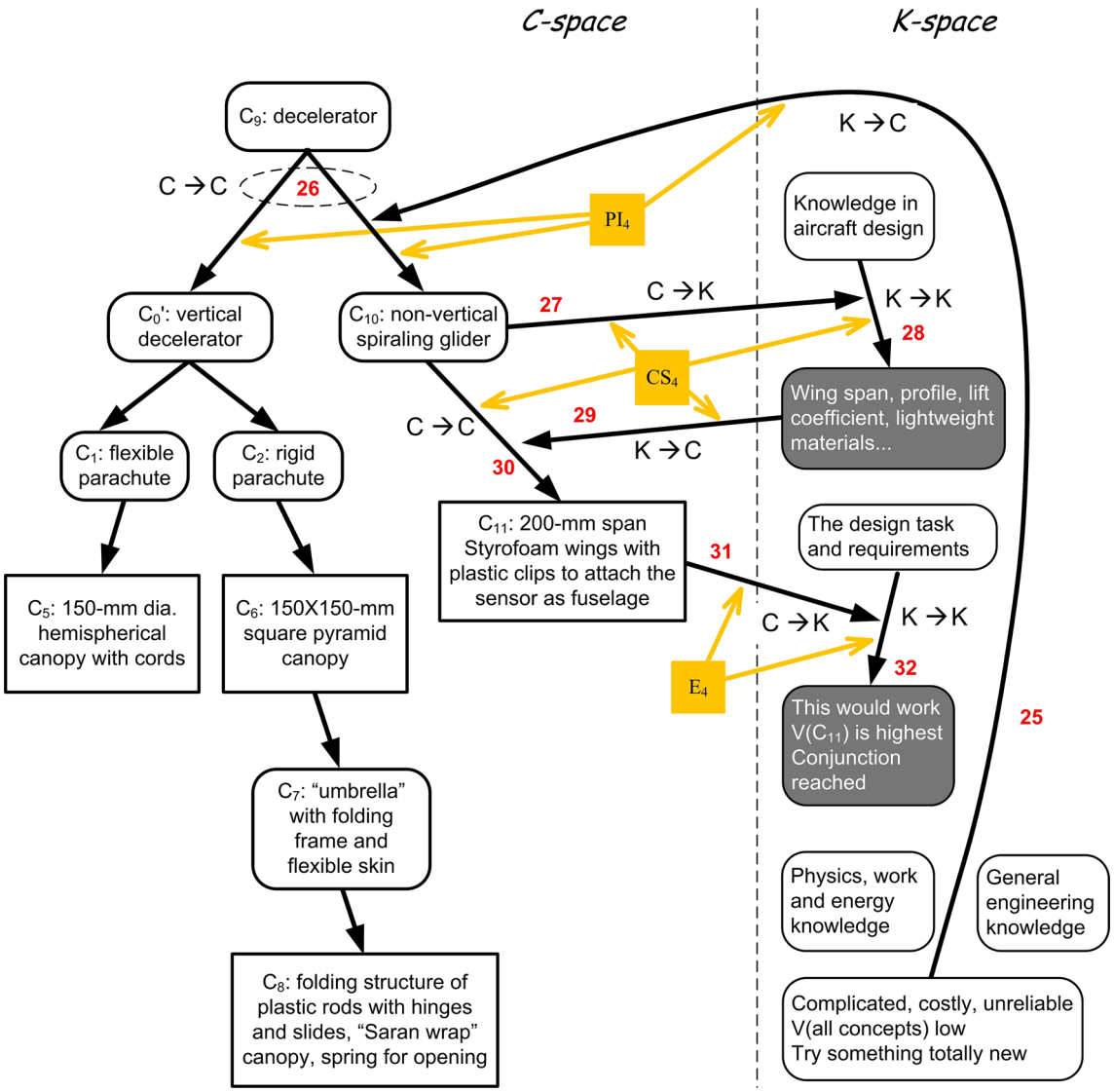



**Fig. 14** C–K model of the fourth PI–CS–E cycle demonstrating a de-partition that leads to a conjunction for the root concept

a breakthrough by creating a totally new design path, and that terminated in success.

Can we consider this design process and its outcome to be optimal or exemplary? Certainly not: There might be even better solutions to this task, and other designers could perhaps have arrived at the same solution quicker. We cannot even say that each of the designers' decisions and choices was the best possible one. Nevertheless, we can observe many fundamental design activities that are not specific to using PA: looking for existing solutions to similar problems, selecting among alternatives, pursuing a concept through several iterations of refinement, reaching a dead-end, reasoning at the level of first principles, embodying ideas in hardware representations, evaluating the design artifact and learning while designing. This means that the modeling and interpretation proposed in this paper may be applicable also beyond the specific design method used here.

One aspect of the decelerator design task that deserves a short discussion is fixation. As many solution-driven engineers do (Lawson 2005, p. 182; Cross 2006, p. 7), the designers of the decelerator also began with straightforward, both well-known and less-known solutions for vertical descent (parachutes, balloons). They did not even consider non-vertical descents and certainly did not think of all the known solutions (e.g., spinning Samara seed-like devices, motorized mini "helicopters," and streamers, the kind of ribbons sometimes used in model rocketry instead of parachutes). The phenomenon of picking a limited number of known solutions and persevering with them is usually referred to as fixation and is often reported as limiting the designer's ability to innovate (Jansson and

Smith 1991; Linsey et al. 2010; Hatchuel et al. 2011). In this paper, we also refer to the sudden realization that vertical descent devices were not the only solution and to the subsequent creation of a new design path as recovering from fixation. However, it should be noted that most engineers rightly attempt to solve problems with known means first and only resort to innovative solutions when the conventional ones will not do. Furthermore, elaboration of an initial concept through cycles of evaluation and modification is PA's prescription for doing design and can also be viewed positively as exhibition of commitment.

### 5.2 Using C–K theory to interpret PA design "moves"

C–K theory has been clarified by this study with regard to its spaces and operators. By letting the elements of C-space correspond to both PA's parameters (concepts) and configurations (structures), a rigorous and consistent model of PA in terms of C–K theory has been derived. The following structure of a C–K concept makes a distinction between two types of attributes: "there exists an object *Name*, for which the group of ideational attributes $P_1$, $P_2$,… can be made with the group of structural attributes $S_1$, $S_2$,…". The ideational attributes correspond to PA's parameters and the structural ones to PA's configuration items. For example, concept $C_8$ in Fig. 14 can be described as:

> There exists an object $C_8$, for which the group of ideational attributes
> $P_1$ = produces vertical drag (inherited from $C_0'$)
> $P_2$ = based on rigid parachute (inherited from $C_2$)
> $P_3$ = built as an umbrella, i.e., folding frame and flexible skin (inherited from $C_7$)
> can be made with the group of structural attributes
> $S_1$ = 150 × 150-mm square pyramid canopy (inherited from $C_6$)
> $S_2$ = constructed of plastic rods, hinges, slides, Saran-wrap and spring.

The last attribute, $S_2$, is the configuration item added to $C_7$ in response to the parameter $P_3$ to form concept $C_8$. The interesting thing to note is that except for the root concept in C–K (which is not defined as a PA entity), all other concepts have some attributes. But because a C–K concept can be either a PA parameter or configuration, and as PA excludes the possibility of having configurations without parameters to support them, the concepts in C–K sometimes have only ideational attributes, and sometimes ideational plus structural attributes; however, a concept cannot have structural attributes and no ideational ones.

All three PA design moves have been modeled in terms of sequences of the four C–K operators: PI corresponds to the pair [K → C, C → C], CS is the quartet [C → K, K → K, K → C, C → C], and E is the pair [C → K, K → K]. It can be seen that although PA's fundamental entities, concepts and configurations, belong in C–K's C-space, all three PA moves require a visit to K-space. K-space contains existing knowledge in the problem domain and related areas, and also meta-knowledge—knowledge about the design process itself—although this last item was not shown in the diagrams of this paper. More importantly, K-space is where learning is carried out during the design process by evaluating the evolving artifact, deducing its behavior, assigning values to all pending concepts and generalizing this new knowledge to form a decision as to how to proceed.

The role of PI, parameter identification, as the most important step in PA has also been clarified. PI consists of identifying, through the learning facilitated by successively evaluating configurations, what the relevant new parameters to be kept are, i.e., to be considered as the defining ideas for the concept. Note that "identification" in PI carries the meaning of a *design* action, and not just a selection in a decision making process, since the concept keeps changing. Some attributes are identified and selected in K-space when forming a configuration (in the CS step), but the most influential step on the final outcome is adding ideational attributes in C-space to generate new concepts.

Some basic notions of C–K theory have also been clarified by this study. It has been shown that K → K operators represent deductive reasoning, generating new knowledge from existing one, but their action needs to be triggered by a reason, a purpose, and this is represented by a C → K operator. Such activation of a K → K operator takes place in two cases: first, as part of a CS step, where the meaning is searching for the knowledge needed to implement an idea as a configuration, for example, using the drag force formula to calculate the parachute diameter given the weight and desired rate of descent. The second case is during an E step, meaning looking for the knowledge needed to deduce the behavior of a configuration. (An exception to this triggering of K → K is the steps marked with a "1" in Figs. 4 and 11, denoting the transition from the preceding need analysis or task clarification stage to conceptual design.) Likewise, a K → C operator uses knowledge for initiating a C → C operator. As demonstrated in this study, C → C operators do exist, representing the derivation of a new C–K concept from another while inheriting its attributes. However, this operation does not happen by itself in C-space, only if activated by a K → C operator, as part of a PI or CS step. This validates C–K theory's premise of mutual expansion: K-space is responsible for the expansion in C-space, but perhaps somewhat surprising, C-space drives the generation of new knowledge—the learning—in K-space.

Another issue clarified is that the tree structure of C-space is not chronological, as demonstrated by the de-

partition that took place. To capture the time-dependence of the design process, C–K's concepts were labeled with a running index and the operator arrows numbered. One of the fundamental notions of C–K theory is that everything in C-space represents "undecidable" entities, but once a "true" or "false" logical status is assigned to it, this entity becomes knowledge and "moves" to K-space. The interpretation of this notion in the current paper is that concepts in C remain undecidable even when the designer finds them deficient and abandons their further development in favor of pursuing other paths. For example, concepts $C_5$ and $C_8$ of Fig. 14 are still present although their development was stopped due to their low value, as determined by the corresponding evaluation steps. This means that the designers could return to these concepts at a later stage, if their value increased through learning new knowledge.

### 5.3 Steepest-first exploration

At two distinct steps of the design process, the designer is required to make a choice or selection among issues at the functional or conceptual level. First, during TI, the designer examines the design task with the aid of added understanding gained during need analysis, to identify the most difficult aspect of the task. The methodology directs the designer to begin the design process with that issue, as demonstrated by choosing "deceleration" for the root concept. The second step requiring such selection is PI, activated at every cycle of PA by the preceding evaluation. Here, the designer should consider the "most critical conceptual-level issue" of the moment.

At both instances, the selection represents an efficient strategy of depth-first that is quite unique: Instead of getting the easier aspects out of the way first and handling the more difficult issues later, as might seem reasonable in general problem solving, or perhaps addressing *all* the issues simultaneously, as in systematic design, the PA methodology sends the designer in the "steepest" direction. This heuristic rule is based on two insights. First, there is the recognition of the function–form dependence in design, which means that a structure created to provide some function usually results in new behaviors, themselves requiring structural modifications, and so on (Gero and Kannengiesser 2004). To make this potentially endless cycle more manageable and efficient, it makes more sense to address the higher-difficulty aspects first, assuming that the easier needs will be satisfied later in a way that complies with the already-solved problems.

The second insight inspiring the "steepest-first" heuristics is the fact that most designers form quite early an underlying core concept and keep pursuing it even when faced with implementation difficulties. This realization was central to forming the original PA methodology by observing designers (Li et al. 1980) and has been confirmed by both anecdotal evidence and empirical studies of practicing designers. For example, Cross (2004) calls this central idea the "principal solution concept" and Lawson (2005) names it the "primary generator idea." This fundamental design idea dominates the rest of the functional aspects and therefore needs to be addressed early. Most of the critical issues with the evolving design cannot be identified upfront, but rather arise as the design unfolds according to the main idea.

In compliance with the "steepest-first" strategy, issues of packing, deployment, etc. were put off during the TI stage of the decelerator design example. Clearly, if the decelerator itself is still undefined, one cannot design its means of packing and deployment; nevertheless, these secondary issues were not completely ignored when designing the decelerators themselves. The initial "central idea" was using flexible parachutes, but it was abandoned quite early, perhaps indicating that the student designers were not experts. A more experienced designer might have addressed the new critical issues of opening the parachute and tangling of the cords while keeping the original concept. He or she could, for example, introduce means of forcing the parachutes to open using the airflow created by the airplane's movement, or mechanically pulling on the canopies with static lines.

The most critical aspect identified with the next central idea (rigid parachute) was the packing of relatively large, non-nesting structures. The decision to opt for an umbrella-like foldable configuration could not have been made earlier, when thinking of flexible parachutes. Furthermore, the implementation with plastic rods, hinges, etc. facilitated the identification of cost and reliability as key drawbacks. Here, again the designers could have chosen to modify the current concept by thinking of ways to simplify the structure, perhaps looking at cocktail umbrellas or the art of origami. Instead, they generated another central idea, that of a glider.

The steepest-first strategy is an inherent part of the PA method, constituting meta-knowledge that resides in K-space and originates from training and practicing the method. The current interpretation through C–K theory and the analogy to B&B, however, allow us to suggest that this strategy is in fact carried out through the repeated application of evaluation steps. When faced with a need to pick the "most critical issue" among several choices, the selection will be of the issue that could potentially reduce the uncertainty most steeply and therefore generate more value for the resulting concept.

### 5.4 Design path evaluation

A significant result of this study is that the PA design process is controlled by a learning-based state and path evaluation function that is responsible for both the efficiency and innovative capability of the inherent strategy. For evaluation to be credible and useful, PA encourages the designer to quickly implement ideas as hardware representations and not rely on assessing abstract ideas. In this sense, the strategy resembles the use of (virtual) rapid prototypes as an aid to the design ideation process. Such rough sketches of prototypes with initial sizing and perhaps other specified properties represent the current state of the solution and can readily be evaluated. In some cases, simulations and physical models are needed for testing and experimentation. Even more important, the design path that has led to the current state can also be assessed, with the robustness of the evaluation results constantly increasing by learning. Comparing PA to OR's and AI's B&B family of search algorithms, the former exhibits a more general strategy wherein the evaluation function is not fixed a priori, nor does it change algorithmically, but rather, it is based on a process of learning during design and can be modified accordingly at any time.

At the beginning of the process, during the TI stage, technologies for the core task are proposed, their advantages and drawbacks listed, and a selection of the best candidate is made. Although this is clearly an activity of evaluation, there is still no learning involved, and it only serves to tentatively point in the general direction or path of the design development to initiate the PA process. In fact, PA's depth-first with backtracking allows changing the initial choice quite easily, as demonstrated in the decelerator example. Moreover, the final design does not necessarily have to be based on one of the core technologies identified at the outset. In the decelerator example, the designers listed parachutes and balloons and ended up with an original concept of a spiraling glider. In general, if we use the term "innovative" to describe solutions that are not based on the core technologies known at the beginning of the design process, two mechanisms for innovation have been revealed through the C–K interpretation: (1) looking for a new technology (this has not been demonstrated by the decelerators example but is depicted in Fig. 9) and (2) re-examining the root concept and de-partitioning C-space.

C–K modeling, however, reveals much more about the E step. In addition to looking at the latest version of the evolving design and judging the extent to which it works properly and satisfies the design task requirements, it also examines the whole design path which is included in the concept description. The ideational attributes of the evaluated C–K concept constitute a trace of the stream of consciousness, the flow of thoughts, from the root concept to the present state, while the structural attributes form the description of the physical artifact. The designer can conclude that the current configuration represents a conjunction for the root concept, and then the design is complete, or that there is a disjunction and the process should continue. In the latter case, the exact reason can be identified: It may be a specific $S_i$ (a structural attribute) that needs to be modified or a $P_j$ (ideational attribute) that now turns out to be problematic. Accordingly, the decision about how to proceed will address the pertinent issues.

Learning-based evaluation has been demonstrated through the case study of this paper. Choosing the flexible parachute concept ($C_1$ in Fig. 12) was equivalent to forming a hypothesis that a solution based on this technology was feasible. To be tested, that hypothesis needed to be refined by embodying the idea in specific hardware ($C_5$). The evaluation at that moment addressed two issues: (1) did the specific hardware represent a good solution and (2) was a solution based on flexible parachutes reachable? The designers' conclusion, that the 150-mm diameter hemispherical parachute presented significant shortcomings, was translated into a low value for the whole design path of flexible parachutes and a corresponding decision to attempt another technology whose value was higher.

In the second evaluation, that of rigid parachutes, drawbacks of the configuration were initially addressed by keeping the design path and attempting to modify the concept. Only during the next evaluation step, $E_3$, the designers had already learned enough to assign a low value to both the flexible parachute and rigid parachute paths and conclude that they should take a fresh look at the underlying physics. Moreover, the two untried design paths of using balloons were also put aside (again, through assignment of low values) in light of the newly learned insight regarding vertical versus non-vertical descents.

Evaluation in PA can therefore be generalized as follows. A configuration that consists of a C–K concept of the form $C_i$ ($P_1$, $P_2$,…, $P_m$, $S_1$, $S_2$,…, $S_n$) is given. The hardware description ($S_1$, $S_2$,…, $S_n$) is examined to reveal whether it would work properly and satisfy the design requirements. If the answer is "yes," then the design is complete. Otherwise, some undesired behavior has been detected because something is still missing or a problem is discovered. If the value of the current concept is still higher than all other concepts, the design process should continue by modifying the set ($P_1$, $P_2$,…, $P_m$), which is the ideation sequence in the design path. If the evaluation shows that the design path as a whole is good, then it is kept and the design process continues along it. A relatively minor modification would be an addition of a new ideational attribute $P_{m+1}$, followed by implementing it as a new structural attribute $S_{n+1}$. Or perhaps the current problematic aspect can be resolved by backtracking to a previous

decision point, changing the path slightly from $P_m$ to $P'_m$, and realizing it as $S'_n$ instead of $S_n$.

However, it may well happen that examination of ($P_1$, $P_2$,…, $P_m$) will trace the current problematic situation to as early as $P_1$, meaning that the whole design path is undesirable. Clearly, this can happen by the designer making a mistake when generating $P_1$ in the first place, or it can represent a learning process: an original thought that was correct at an earlier time turns out later to be wrong, after acquiring new knowledge by means of the actual activity of designing. Backtracking to the beginning of the design path is a major shift in the design process and is carried out through reasoning about the whole concept space and at the ideation level (PA's parameters). It can lead to choosing another technology already listed as a possible candidate or to searching for a yet-unknown technology, or even to re-examining the validity of the root concept and attempting a de-partition.

The innovative capability of PA's strategy has been attributed to de-partitioning in C-space, facilitated by the extensive learning during the concept development process, which in turn refined the evaluation function. PA allowed recovery from the effect of the initial fixation by learning accomplished through the repeated generation and evaluation of "standard" configurations during the design process. This learning manifested itself in the production of new knowledge, or K-expansions in C–K terms, and discovery of a final solution that was not included in the fixation-affected initial set of technologies. Moreover, the important attribute responsible for the de-partitioning was the vertical descent, and this was implicit—either ignored or unrevealed—at the beginning, when proposing concepts $C_1$ to $C_4$. Only evaluation based on learning helped discover the criticality of this attribute, which was subsequently subtracted from the properties of the emerging concepts. This generalization in the definition of the root concept—de-partitioning or inclusion in C–K terms—has been identified as the exact mechanism though which innovation was achieved.

The learning process and the way the design progression is controlled by the evaluation, as described above, are similar to the more rigorous presentation in Ullah et al. (2012). They attribute the learning in design modeled with C–K theory to an increase in epistemic information content due to the presence of undecidable concepts. When the designer is unable to reduce the information content in the current path, a different path is attempted.

It is also interesting to compare PA's strategy to classical systematic design methods. In the latter, extensive design work at the functional, conceptual and more detailed levels would have taken place before carrying out an evaluation that could lead to a similar de-partitioning. PA, on the other hand, does not postpone the evaluation; rather, it is incorporated in every step—including evaluation of the design path—and becomes more robust as the design unfolds due to the built-in learning.

### 5.5 Practical implications for PA

Studying PA with C–K theory helps to answer some common practical questions regarding this design method: How can one prioritize the unknown issues? How efficient is PA? When is PA applicable? What are its limitations? We briefly address these issues below.

As elaborated in Sect. 5.3, prioritization to determine the present most critical issue depends on the designer's knowledge, experience and skill. There is no one "correct" way to prioritize, and different designers may derive different results. However, the learning process embedded in PA helps to re-discuss the initial choices and change them as needed and as might become apparent to the designer at later stages of the process.

The claim that PA incorporates an efficient strategy is clarified by the analogy to B&B. Just as the latter helps to avoid exhaustive explorations of complete search spaces, PA guides the designer to move in the most promising direction, and this is explained as the logic of implicit value assignment. We can therefore see this as a form of B&B extended to design processes. Because it appears that the efficiency and exploration capacity of the PA method depend on the value assignment logic, a possible improvement of PA may be to ask its practitioners to try to explicate the value assignment, or it may be possible to clarify different PA strategies associated with different value assignment logics. For example, an approach similar to "General-Opinion and Desire" (GD) proposed in Ullah (2005) may help assign values to alternative concepts in a structured way. GD provides means to encode the extent to which a concept is both known and desirable using several criteria and linguistic input information provided by the designer.

We can now begin to specify some features of PA's domain of relevance and limitations. PA is neither specifically adapted to situations where the goal of the design process is to use only known solutions (i.e., routine design tasks) nor to generating intentionally many breakthroughs purely for the sake of innovation. Rather, PA is oriented toward efficiently and quickly finding a good solution. If known technologies suffice, PA will support a design using them. If known solutions are unsatisfactory, PA will allow discovering other technologies and possibly new perspectives on the design task, leading to a breakthrough.

One possible limitation of PA stems from its depth-first strategy: If a good solution is reached, the designer will

probably stop with that and not explore other options. Clearly, the PA process may be deliberately applied to other technologies to generate alternative solutions, but it would never be as exhaustive as morphological approaches, for example. Moreover, PA seems to require more skill and ability from the user than systematic design methods such as in Pahl et al. (2007). As we have seen, the judgment needed to continually prioritize critical issues and evaluate partial solutions plays a significant role in PA, and may be more demanding than systematically addressing all pertinent functional issues, creating numerous combinations of solution concepts, and finally selecting among them.

## 6 Conclusion

C–K theory was shown to be able to model PA's steps, which are fundamental design "moves": generating an idea, implementing the idea in hardware representation and evaluating the configuration. It also showed that PA supports innovative design by providing a means for recovering from fixation effects. Conversely, PA helped to clarify the structure of C–K's concepts, operators and C-space itself, and to emphasize the importance of K-space expansions.

C–K theory is, by definition, a descriptive model of design and does not contain a strategy for designing. However, it is capable of providing explanations to what happens during design and interpreting the strategy of specific design methods. The main results of this study are the explanation of PA's strategy as steepest-first exploration, controlled by a learning-based design path evaluation. These have been clarified by applying C–K theory and some search-related notions from OR and AI, and demonstrated with the decelerator design case study.

Several interesting issues remain for future research. We have not touched in the present work the cognitive aspects of identifying critical conceptual design parameters and the taxonomy of the knowledge involved. In other words, what particular knowledge and capabilities are required of the designer when making the various decisions, and what exactly happens in K-space during PA as related to the structures of knowledge items and their role as drivers of the design process? In addition, it might be useful to try to identify additional innovation mechanisms in PA that can be explained with C–K theory, and compare PA to other design methods with the tools of C–K theory. An interesting future direction might be the integration of creativity methods, such as TRIZ, in the framework of PA to provide even more innovation capabilities.

**Acknowledgments** The first author is grateful to the chair of "Design Theory and Methods for Innovation" at Mines ParisTech for hosting him for furthering this research. This work was supported by the Israel Science Foundation under Grant No. 546/12.

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Res Eng Design (2018) 29:203–225
https://doi.org/10.1007/s00163-017-0263-6

ORIGINAL PAPER

# Idea-configuration-evaluation (ICE): development and demonstration of a new prescriptive model of the conceptual engineering design process based on parameter analysis and C–K theory

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Received: 6 November 2016 / Revised: 30 June 2017 / Accepted: 1 July 2017 / Published online: 11 July 2017


**Abstract** This paper introduces a new prescriptive model of conceptual engineering design. The model is based on the method called parameter analysis (PA) and the relatively new descriptive model called C–K theory. PA was developed based on observations of designers in action, while C–K theory has a strong foundation in logic theory. The new model combines the benefits of C–K theory and PA to overcome the lack of a strong theoretical foundation in PA and the insufficient prescriptive power of C–K theory. The paper describes in detail the process of developing the new model, which was similar to product development. It started with conceptualization in order to define a set of key factors and principles, i.e., the conceptual foundation or the "ideology" of the new prescriptive model. Next, those principles were integrated into a structured systematic procedure to form the new prescriptive model. The conceptual design of a realistic design task is used to demonstrate the application of the new model. The significance of the current work is the contribution to the theory and practice of engineering design, eventually leading to improved design processes and better designed products. Reporting on the experimental testing of the new model will follow in the future.

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**Keywords** Conceptual design · Design process model · Parameter analysis · C–K theory

## 1 Introduction

### 1.1 Motivation

The importance of the conceptual design stage within the process of engineering design of a new product is well known. This stage is considered the most important in terms of its effect on the success of the final product. At the end of the conceptual design stage, approximately 70% of the product cost and performance are determined, while only about 10% of the development cost has been expended (Ullman 2010). In a competitive world, companies, and organizations that engage in research and development of products and technologies must continuously improve their design process. A better understanding of the conceptual design stage, achieved through research, will lead to products with better quality and value and shorter time to market.

There are two principal questions about the engineering design process (Roozenburg and Eekels 1995): "What is the essential structure of designing?" and "How should the design process be approached to make it effective and efficient?" In regard to these two questions, there are two main kinds of engineering design process models: descriptive and prescriptive. Descriptive models are designed to answer the first question. They aim to understand and explain how designers actually work, i.e., what processes, strategies, and methods they use. Prescriptive models aim to answer the second question via development and validation of systematic procedures that are based on descriptive models.

Considerable research effort in design theory has been devoted to furthering our understanding of design

processes and offering a theory, model, or method for the design process. Unfortunately, most of those theories and frameworks are not widely used in industry. Moreover, since the intention behind most descriptive models is that they should eventually be used as a prescription for design, i.e., becoming a design method, it is sometimes unclear whether a model is descriptive or prescriptive (Blessing and Chakrabarti 2009). Most existing prescriptive models for conceptual design in both academia and industry are based on German research into "Systematic Design" from the 1970s, with several British and American adaptations. This prescriptive model offers a systematic procedure for conceptual design, known as functional decomposition and morphology (Pahl et al. 2007). However, in recent years, this conceptual design process model has been criticized, mainly regarding its inability to capture the dynamics of the design process and as a result, hindering creativity and innovation (Chakrabarti and Bligh 2001; Hatchuel and Weil 2003; Kroll 2013).

For cases requiring innovation, the parameter analysis (PA) method has been proposed (Kroll et al. 2001). However, "prescriptive models are premature until they can be based on validated theory" (Finger and Dixon 1989) and indeed the main drawback of PA is that the method lacks a strong theoretical foundation, so it is difficult to establish its "correctness" and its relation to other design methods. In addition, the method's definitions and basic notions sometimes lack in clarity and precision. Therefore, our objective was to generate a new prescriptive model for the conceptual engineering design stage, based on the theoretical foundation of C–K theory and the empirically derived procedure from PA. The proposed model is intended to overcome the aforementioned drawbacks of PA and the insufficient prescriptive power of C–K. Despite the uniqueness of C–K theory in describing creative and innovative design processes, it does not guide the designer as to what to do next at any given moment. Therefore, a primary objective of this study is linking theory to practice, a need emphasized by Andreasen et al. (2014). The goal of the current research was therefore to produce a practically oriented, easy-to-apply, and effective model that (1) presents a clear and concise step-by-step procedure; (2) is conducive to teaching and practicing design; and (3) captures the dynamics of the design process, thus facilitating creativity and innovation, as well as high-quality and viable conceptual design, with respect to design requirements and other aspects.

### 1.2 Parameter analysis (PA): a brief overview

PA (Kroll et al. 2001) was developed at MIT in the 1970s. The method focuses on the conceptual design process and consists of a descriptive model (based on observations of the design process) according to which the conceptual design process is performed by back-and-forth movement between two spaces: conceptual-level issues in the concept space, and description of hardware (diagrams, sketches, or other representations of physical objects) in the configuration space. Movement from one point to another in the configuration space represents a change in the physical description of the evolving design, but requires conceptual reasoning, which is performed in the concept space. The concept space deals with "parameters," which in this context are functions, ideas, and other conceptual-level issues that provide the basis for anything that happens in the configuration space. Moving from the concept space to configuration space involves a realization of the idea in a particular hardware representation. Subsequently, specific hardware serves to stimulate a new conceptual thought, which results in moving back from the configuration to concept space by abstraction.

PA implements the descriptive theoretical model by a prescriptive model that has three distinct steps. The first step, parameter identification (PI), represents the generation of a new design parameter, i.e., a new or improved concept/idea concerning the most dominant issues at any given moment during the design process. The second step, creative synthesis (CS), represents the creation of a physical configuration based on the issue recognized within the previous PI step. The third step, evaluation (E), triggers the move from the physical realization in the configuration space back to parameters in the concept space. The three steps are applied time and again, constantly reevaluating the information associated with the evolving artifact. At each cycle of this process, the identified parameters are different, as are the changing configurations and the results of the evaluations.

### 1.3 C–K theory: a brief overview

C–K theory was proposed by Hatchuel and Weil (2002, 2003, 2009) and Le Masson et al. (2010) and has gained considerable interest in the design community. The theory is a general descriptive model with a strong logical foundation, considered to capture fundamental properties of the design reasoning process, resulting in powerful expressive capabilities. The theory models design as an interplay between two spaces, the space of concepts (C-space) and the space of knowledge (K-space). Four operators are used to describe movement between and within the spaces: C → K, K → C, C → C, and K → K. K-space contains all established or true propositions, which is all the knowledge available to the designer at any given moment. C-space contains concepts, which are undecidable propositions (neither true nor false) relative to K (K-relativity), representing objects whose existence is not

guaranteed in K. A concept has the structure $C(P_1, P_2, \ldots)$, where $P_i$ is a property or attribute. K-relativity of the concepts is a key notion: decisions regarding the status or goodness of a concept depend on the knowledge that the designer has at a given moment, but this knowledge changes during the design process. Consequently, the same concept can be judged or rated differently upon revisiting it.

Design processes aim to transform undecidable propositions into true ones by jointly expanding spaces C and K through the action of the four operators. This expansion continues until a concept becomes an object that is well defined by a true proposition in K. Expansion of C-space yields a tree structure, while that of K produces a more richly networked pattern. It should be noted that the only operation on concepts allowed by C–K theory is adding or subtracting attributes, and this means that the concept tree is not necessarily chronological, and that it definitely does not represent a decomposition of an initial concept, but rather an expansion of the concept space.

### 1.4 Other design models

Extensive reviews of descriptive and prescriptive models can be found in Finger and Dixon (1989), Cross (2000, 2004), Blessing and Chakrabarti (2009), and others. According to Blessing and Chakrabarti, there seem to be many more descriptive studies, attempting to deepen our understanding of existing design processes, than prescriptive investigations that propose specific methods and steps to accomplish a good design process. However, the distinction between descriptive and prescriptive models may sometimes be vague and depends on their purpose: if the intention is to understand design-related phenomena, then the model will be descriptive; if the intention is for the model to be used in practice, then it will be prescriptive.

A basic and general model proposed by Jones (1963) defines the design process as comprising three stages: analysis, synthesis, and evaluation. Cross' model (2000) from 1984 is based on the essential activities that the designer performs, and proposes a four-stage model of the design process: exploration (needs analysis), generation (conceptual design), evaluation (checking or evaluating design proposals and deciding on a final version for manufacture), and communication (preparing documents for product manufacture). French's model (Cross 2000) from 1985 is similar to Cross' model and is based on the following activities: analysis of the problem, conceptual design, embodiment of schemes, and detailing. The FBS model (Gero and Kannengiesser 2004) comprises three classes of variables describing different aspects of a design object: F-function, B-behavior, and S-structure. The model identifies several processes within design, such as transforming functional requirements into expected behaviors, transforming expected behaviors into solution structures, deriving actual behaviors from structures, comparing derived with expected behaviors, and responding to unsatisfactory behaviors by reformulating the design space. This model appears to enable an iterative and nonlinear process, which is intended to capture the dynamics of the design process.

Another type of model considers mathematical formulations of design: general design theory (GDT) (Yoshikawa 1981), axiomatic design (AD) (Suh 1990), coupled design process (CDP) (Bracha and Reich 2003), and infused design (ID) (Shai and Reich 2004). According to Bracha and Reich (2003), mathematical models can improve our understanding of the limits of formalizing design and its automation and could produce practical guidelines for implementing design procedures or systems.

Among the more prescriptive models, the functional decomposition and morphology method of Pahl and Beitz from the 1970s is considered to be the cornerstone for work on the engineering design process, and their book (Pahl et al. 2007) is the basis for many engineering design classes and practices. The model, which prescribes a sequence of major stages for the design process, includes abstraction of the important problems, functional analysis by decomposing the main function into finer and finer independent sub-functions, creation of solution principles or "sub-concepts" for each sub-function, and finally, assembling the sub-concepts combinatorially to form multiple overall design concepts. Other well-known models include the "waterfall model" from software engineering (Pressman 2001), the V-model from system engineering (Forsberg and Mooz 1991), Pugh's method (1991)—commonly used for concept selection although originally intended to be a complete design method, Brainstorming (Osborn 1963), which is used as a method for collective creativity, and TRIZ (Altshuller 1984), which is based on identifying design contradictions (technical and physical) and eliminating rather than accepting them. Two recent papers (Chen et al. 2015a, b) present a new model of conceptual design named need-function-principle-system (NFPS). The model elaborates the conceptual design process in five stages: clarification, synthesis, embodiment, analysis, and prediction. It explains prescriptively how a need is transformed into functions, then the functions lead to abstract solution principles, and finally a structure emerges.

To summarize, there are many existing models of design, some are more descriptive and some prescriptive. Some models tend to be process-centered, focusing on stages and activities, while others are product-centered, emphasizing the characteristics that the product should have. There are comprehensive models with a wide scope and there are models that focus on specific parts or aspects

of the design process. Many models include iterative and recursive activities and contain synthesis and evaluation stages. Evaluation sometimes consists of selection among alternatives and sometime analysis of a single entity with the help of some criteria. The design process tends to diverge at the beginning but must converge at the end.

The design process is a map of how to get from the need to the final product. This process requires basic knowledge in science and engineering, but also uses systematic procedures—prescriptive models—so that the final product will be innovative and of high value.

### 1.5 The importance of using a theory and C–K theory in particular

The purpose of any theory, including design theory, is to describe, explain, and predict phenomena. The importance of a theory in design research and for the development of prescriptive models is paramount, as long as the theory is considered acceptable. Reich et al. (2012) write that enhancement of design methods should rely on in-depth analysis and be driven as much as possible by theories. Badke-Schaub and Eris (2014) refer to design theory as "a body of knowledge which provides an understanding of the principles, practices and procedures of design. That knowledge leads to hypotheses on how designers should work, and such hypotheses provide the basis for the prescriptive part of design methodology." Cavallucci (2014) emphasizes the practical use of design theory in providing a scientifically proven and methodological theoretical foundation for appropriate use and practice.

Theory as a precise conceptual framework can provide an explanation as to why different methods perform differently and propose changes to improve them. The theory can provide new or different perspectives on issues that were previously unclear or that must be implemented in order for the prescriptive model to be successful (for example, what is the trigger for new ideas, what are the relevant design spaces, what are the design steps or activities, what are the necessary conditions for creativity and innovation, how is a decision made, how should the solution direction be chosen, etc.). Another advantage is that strong reliance on acceptable theory can provide support for the correctness and effectiveness of the model.

We chose C–K theory as our descriptive reference model since it is considered to be a theory that offers comprehensive formalization of the design process, independent of any design domain, and describes creativity and innovation within the same framework as the design processes. The theory appears to capture the dynamics of the design process, and contains the necessary conditions that should be verified by any prescriptive model that is intended to allow creative and innovative performance (Reich et al. 2012; Kroll et al. 2014).

Since its introduction, C–K theory has been used in several studies in connection with other design methods. Kazakçi and Tsoukias (2005) compare C–K theory to Gero's situated design (1996) and suggest adding the designer's environment as a new space. This extension does not change the basic assumptions of C–K theory but offers a practical organization of space K that helps develop new types of personal design assistants. Braha and Reich's (2003) coupled design process is shown to have many similarities to C–K theory, with the latter shedding new light on some of the former's implicit assumptions. Shai et al. (2013) analyze their infused design method with the aid of C–K theory, and show the benefits of developing better understanding of both the method and the theory through such a comparative study. Reich et al. (2012) uses C–K theory to improve the ASIT (a simplified version of TRIZ) creativity method. Hatchuel et al. (2011) compare C–K theory to four other design theories using two criteria: generativeness and robustness. It is shown that the various theories represent an evolutionary development of our understanding of design, and not radical changes. An interesting finding is presented by Elmquist and Le Masson (2009): a failed R&D project for developing an urban microbus is analyzed with C–K theory and the project is shown to make significant contributions to the organization and to the field of the design task. The developers of C–K theory also use the theory to develop a method called KCP for collective creative design (Hatchuel et al. 2009). It has been claimed that KCP contrasts with classical creativity techniques such as brainstorming, and has been successfully implemented in 14 industrial cases. Similarly, Zeiler (2012) uses C–K theory's KCP model to enhance the integral design variant of systematic design, which uses combinations of morphological charts generated by individual designers to form a morphological overview representing the whole team. This work includes empirical evidence that the incorporation of aspects of C–K theory indeed increases the number of solutions generated by the designers.

In summary, C–K theory is considered to be a general descriptive model with a strong logical foundation, resulting in powerful expressive capabilities. It is used in this research for modifying and enhancing the PA method while providing a theoretical foundation and validation support for the new model.

## 2 The R&D methodology

In order to generate a new prescriptive model, we need to know how to perform research on design processes so that the results will be valid and acceptable. Blessing and Chakrabarti (2009) write: "Developing support [support in

this context is a design method] should follow the same best practice recommended for developing products and software. Many aspects of design methodologies can be applied for support development." Based on this approach, the R&D methodology was designed as a combination of Jones' descriptive model (Jones 1963) and guiding principles from the design research methodology (DRM) structured framework (Blessing and Chakrabarti 2009) indicating four distinct stages for conducting design research: research clarification (RC), descriptive study-I (DS-I), prescriptive study (PS), and descriptive study-II (DS-II).

Figure 1 presents the outline of the R&D methodology with the three stages of analysis, synthesis, and evaluation combined with the DRM stages. It incorporates ongoing evaluation by analyzing a multitude of realistic design problems in an iterative process of testing the model, improving it, testing again, etc. The case study demonstrated in Sect. 4 is one of the examples studied.

The first step of the analysis stage began with research clarification (RC in the DRM). This step included a literature survey, continued with an in-depth study of PA and C–K theory, followed by formulation of the research objective, working hypotheses, expectations, and success criteria, and ended by defining the R&D methodology and specific research tasks (R.T.), as follows:

- R.T.#1—Studying the effect of combining C–K theory and the PA method.
- R.T.#2—Redefining key notions and terminology, and reformulating the existing models.
- R.T.#3—Studying and defining the design exploration strategy.
- R.T.#4—Studying and defining the use and composition of design spaces.
- R.T.#5—Studying and defining the design operators for moving within and between design spaces.
- R.T.#6—Defining the new prescriptive model of conceptual engineering design.
- R.T.#7—Testing and evaluating the new prescriptive model (i.e., design experiment with external participants).

The first step above is analogous to need analysis in the case of product development. The analysis stage moves forward according to R.T.#1, which is an in-depth descriptive study (DS-I in the DRM). The main goal in this step was to improve our understanding of all aspects of C–K theory and its interpretation of PA and vice versa. Preliminary outcomes can be found in Kroll et al. (2013).

Similar to the engineering design process, the synthesis stage of developing the new prescriptive model began with conceptualization in order to develop a set of key factors and principles, i.e., the conceptual foundation or the "ideology" of the new prescriptive model. This was followed by R.T.#2–R.T.#5, which are part of the DS-I descriptive study. Having developed the conceptual foundation of the new model, the next step in the synthesis stage was prescriptive in nature, that is, PS in the DRM, according to R.T.#6. What was left to do at this stage was to combine all of the key factors and principles into a structured systematic procedure and formulate a specific model for every stage of the design process. Through ongoing evaluation and refinement (including iterations and re-examination of the conceptual foundation) of different combinations, a viable and promising prescriptive model was realized.

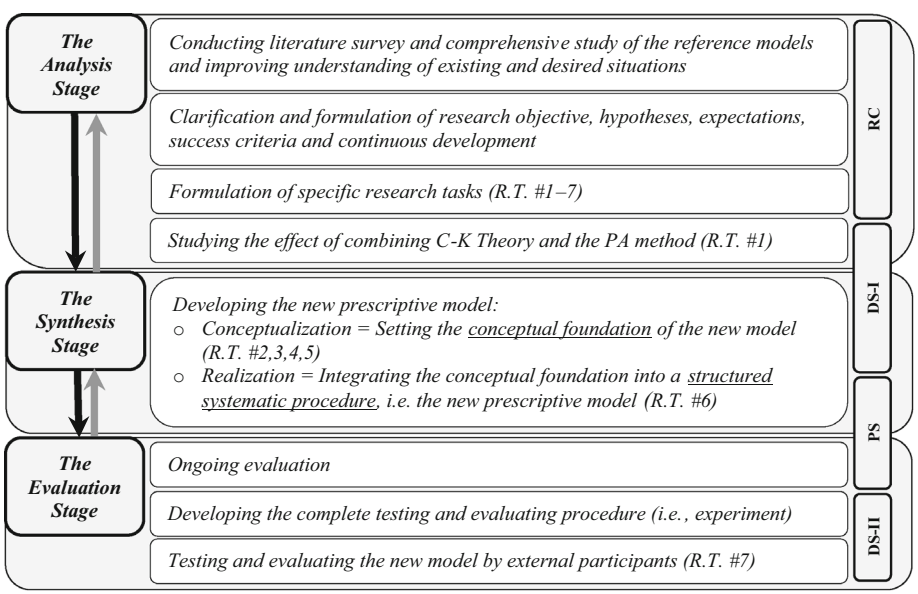



**Fig. 1** The R&D methodology. The *arrows* show that iterations are commonplace between stages, thus the process is not rigid and linear. The DRM stages are shown on the *right* and Jones' stages on the *left*. The research tasks (R.T.) are described in the text

Having defined the new prescriptive model, the next stage is a second descriptive study, DS-II. The new model will be evaluated experimentally by examining the performance of external participants in using it, i.e., R.T.#7. Setting the stage for the experimental work is briefly outlined in Sect. 6, while full reporting will be the subject of a future article.

## 3 The idea-configuration-evaluation (ICE) model

The conceptual foundation of the new model is strongly based on C–K theory and the PA method, but also on general and independent (of any design domain or method) notions and aspects that have been recognized and considered to have a strong bearing on the design process. The outcome is a set of key factors and principles that are integrated to form the new model, as explained below. The resulting model is summarized at the end of this section.

### 3.1 Design task statement and requirements

The model employs the cognitive strategy of solution-focused reasoning (Lawson 1979; Cross 2004; Kruger and Cross 2006). At the beginning of the process, the designer will be guided to spend less time clarifying the design task and requirements, leave the problem somewhat ill-defined, and focus initially on generating alternative solutions. In addition, the model employs the principle of solution–problem co-evolution (Simon 1972; Maher 2001), whereby the design task and requirements are gradually refined during conceptual design. At the end of the conceptual design stage, and before moving the design process to detail design, the problem as well as the scope of the design task and requirements should be finalized and well understood and defined. Accordingly, two types of design task statement and requirements are recognized: initial/ill-defined and final/well-defined.

The above approach is intended to better capture the dynamics of the design process in accordance with Christiaans and Dorst (1992), who found that more successful performance in terms of creativity and quality of the solution is achieved by one who "…asks less information, processes it instantly, and gives the impression of consciously building up an image of the problem…". An additional and perhaps less academic argument can be made through the "business" aspect. Misunderstanding the task scope in terms of development risks, technological maturity, relevant engineering disciplines, required development tests, etc. may lead to financial losses. In practice, the desired situation is that the development proposal responding to the client/customer requirements should be produced after the designer has understood the need, requirements and scope of the design task well. This can be achieved in most cases only after generating a conceptual solution that allows examining its applicability to the need and the given requirements. A similar principle of requirements refinement can be found in the CDP model (Bracha and Reich 2003).

### 3.2 Representing the design artifact: the notion of concept

PA and C–K theory differ in their definition of concept. PA's concepts are "parameters," which are ideas or ideational-level issues such as functional descriptions, physical principles, core technologies, and analogies that shed new light on the design task. They constitute a rationale for evolving the design, but they do not include physical descriptions of the artifact. In contrast, C–K theory uses "concept" as a description of the solution, consisting of undecidable (neither true nor false) propositions. C–K's concepts remain in C-space as long as the design is evolving and has not yet been proven true relative to the knowledge in K-space. PA deals with the parameters in its concept space, and with the physical or the hardware descriptions in its configuration space. C–K theory, on the other hand, deals with the evolving object (PA's parameters and configurations) as a single type of entity in its C-space, whose meaning is "There exists some object $X$, for which a group of properties $P_1, P_2, \ldots P_n$, are true in K" (Hatchuel and Weil 2009). The properties $P_i$ are generated in K-space, and are sometimes ideational in nature and sometimes configurative.

From PA, we chose to preserve the distinction between parameters and configurations. From C–K, we took the notion of a single description of the evolving artifact, the concept. For this purpose, we define the data structure of a concept as $C_i(IA_1, IA_2, \ldots, IA_m, SA_1, SA_2, \ldots, SA_n)$, where $IA_i$ is an ideational attribute and $SA_i$ is a structural attribute. The meaning of concept $C_i$ is that there exists some object $C_i$, for which the ideational attributes $IA_1, IA_2, \ldots, IA_m$ can be realized with specific structural attributes $SA_1, SA_2, \ldots, SA_n$. The ideational attributes correspond to PA's parameters, and structural attributes to PA's configuration items. In the new model, a concept can evolve in two ways:

1. By adding new ideational attribute(s) (IA) and sometimes subtracting existing attribute(s), ideational or structural.
2. By realizing ideational attribute(s) with specific new structural attribute(s) (SA), and actually creating a configuration in PA terms.

The ideational attributes represent the ideas, justifications, and reasoning behind the solution. They should be expressed in terms of physical principles, core technologies, and other ideational-level terms, without a specific

physical or hardware description. They are abstract in nature and created in almost every cycle of the conceptual design process. They can usually be represented by textual descriptions. The structural attributes describe how to realize or implement the ideational attributes as tangible entities, i.e., representations of hardware. They can have the form of a sketch, CAD model, material properties, prototype, or some other specific physical or hardware description. Realization of structural attributes is a design activity that usually requires more time, effort, and sometimes resources. The structural attributes differ from ideational attributes not only in their meaning, but also in their impact on the conceptual solution: they are more temporal during the conceptual design stage, they can change continuously and according to the development of the ideational attributes. Structural attributes are needed mainly to enable quantitative evaluation of the evolving solution, so they may be described quite crudely, only enough to facilitate the evaluation. After completing the conceptual design stage, the structural attributes may be refined in much more detail during the embodiment and detail design stages.

As an example, consider a design task to monitor the number of air-volume exchanges in a room by measuring the air flow through a duct (adapted from Kroll et al. 2001, p. 105). A possible concept can be formulated as: measure the drag force exerted on an object immersed in the flow (the drag force is proportional to the flow velocity squared, so this can provide a direct measure of the flow rate). The drag force can be measured by a strain gage force-measuring transducer. This concept can be written as $C(\mathrm{IA}_1, \mathrm{IA}_2)$, meaning that it has two ideational attributes: $\mathrm{IA}_1$—measure the drag force exerted on an object immersed in the flow, $\mathrm{IA}_2$—the drag force is measured by a strain gage. The concept is next realized by specific structural attributes: $\mathrm{SA}_1$—a circular aluminum disk, 2″ in diameter and 1/32″ thick, $\mathrm{SA}_2$—the disk is rigidly connected to the top surface of the duct through a flat arm, 1/32″ thick, 1/2″ wide, and 3″ long, $\mathrm{SA}_3$—a specific strain gage (model no., type, i.e., foil, wire or semiconductor, etc.). The realized concept $C(\mathrm{IA}_1, \mathrm{IA}_2, \mathrm{SA}_1, \mathrm{SA}_2, \mathrm{SA}_3)$ is shown in Fig. 2.

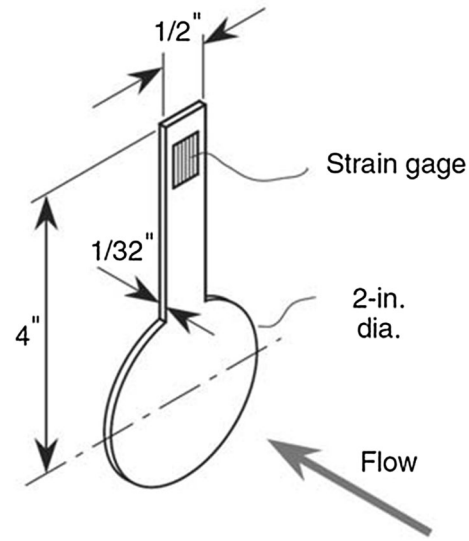



**Fig. 2** Concept $C(\mathrm{IA}_1, \mathrm{IA}_2)$, realized with specific structural attributes $\mathrm{SA}_1$, $\mathrm{SA}_2$, $\mathrm{SA}_3$, resulting in concept $C(\mathrm{IA}_1, \mathrm{IA}_2, \mathrm{SA}_1, \mathrm{SA}_2, \mathrm{SA}_3)$

### 3.3 How should the design process begin: the first concept $C_0$

The first concept $C_0$ is derived from the initial requirements list and refers to the basic functional attributes that the intended product should have. In other words, $C_0$ is a concise expression of the detailed requirements list, mainly in terms of top level functions. The rationale behind this definition is that requirements, which primarily define what the product should do and how well it should do it, are actually an initial expression of concept. The data structure of $C_0$ is therefore written as $C_0(F_1, F_2, \ldots, F_n)$.

As an example, let us assume a need that defines a design task for a stairwell cleaning robot. The basic functional attributes of the intended product can be written as: $F_1$—soap and water filling, $F_2$—autonomous movement upstairs and downstairs, $F_3$—autonomous pick up of dry and loose dirt, $F_4$—autonomous washing of surfaces, $F_5$—unloading of dirt and dirty water. Consequently, $C_0$ is written as $C_0(F_1, F_2, F_3, F_4, F_5)$.

The above definition of $C_0$ is strongly based on C–K theory. Hatchuel and Weil (2003) write explicitly that "in our framework the formulation of the requirements is a first concept formulation which is expanded by the designer in a second concept that is called the proposal." According to C–K theory, a concept is an entity with undecidable logical status, neither true nor false, at the moment of its creation. There is no concept *per se*, but relative to some knowledge. The task of design, or the "intention" in C–K terms, is built into the definition of a concept. In other words, if a need, which is expressed by a list of requirements (functions and constraints), can be met by an existing product without any changes or modifications, then there is no conceptual design task and certainly no innovative design process. The design process aims to generate an object that does not exist relative to existing knowledge. Hence, $C_0$, which is a concise expression of the detailed requirements list, is actually an initial expression of concept.

It should be noted that $C_0$ is not explicitly provided to the designer and should be generated from the initial engineering requirements. In typical design situations, it is not always easy to decide or recognize at the beginning of

the design process, from the initial design task and requirements, what are the basic functional attributes that the intended product should have. Previous experience and knowledge can be useful, but this is not the main point or a necessary condition. The main point is that in "real life," some functions as well as critical design issues can only be discovered in the context of a particular solution. This is consistent with the principle of solution–problem co-evolution, so there is definitely a possibility that during the conceptual design stage, some of the basic functional attributes will be consolidated or changed, or other unexpected ones emerge (see evaluation decision 5 below).

### 3.4 Design exploration strategy

The model employs the design exploration strategy of steepest-first (Kroll et al. 2014) concerning the most difficult and challenging aspect(s) of the design task, combined with an ongoing iterative process of divergent thinking about ideational attributes and convergent thinking regarding structural attributes.

#### *3.4.1 Steepest-first strategy*

After creating $C_0$, the designer should focus first on the most difficult and challenging aspect(s) of the task, those that make the design task a concept relative to the existing knowledge. The main argument for justifying this approach is based on recognizing the function–form dependence in design (Gero and Kannengiesser 2004). This means that a structure created to provide some function usually results in new behaviors, themselves requiring structural modifications, and so on. Hence, in order to increase the effectiveness and efficiency of the design process, it makes more sense to deal first with the most difficult and challenging aspects, and assume that the easier ones will be satisfied later in a way that complies with the previously solved issues. However, despite following this "steepest-first" strategy, the designer should constantly evaluate the evolving solution relative to all the design aspects and the requirements behind them. This ensures that the solution created to provide one function of $C_0$ will be compatible with the others, and conflicting solutions avoided.

The steepest-first strategy is maintained throughout the concept development process. When weaknesses in a concept are uncovered by an evaluation step (see Sect. 3.6), the more challenging of those should be addressed before proceeding with resolving easier aspects.

#### *3.4.2 Divergent and convergent thinking*

Due to the ongoing iterative nature of the design process, and in accordance with the distinction between ideational and structural attributes, the model implements the strategy of "breadth thinking" concerning ideational attributes and "depth thinking" concerning structural attributes. The practical implication of this approach is that the designer is guided—depending on feasibility and necessity—to generate several alternative ideational solutions regarding the most difficult and challenging aspect(s) of the design task or the most critical issues of the moment. By cursory evaluation of the alternatives, perhaps by reviewing their pros and cons and using general and qualitative criteria, the designer should then determine which has the better chances of resulting in a successful solution. The most promising ideational alternative will be selected for further refinement and realization with structural attributes. It is the nature of design processes that the usefulness, necessity, and variety of alternative ideational solutions decrease as the process unfolds and converges towards a final conceptual solution.

The main arguments for justifying this exploration strategy are as follows:

- There may be a legitimate question of why to select among the alternative solutions and not refine them all in depth and make the selection at the end of the process. We believe that evaluation that takes place continuously during the design process, together with the possibility and flexibility of backtracking at any given moment, should be an integral part of the process control and learning that take place during design. This evaluation increases the likelihood of screening and filtering the evolving concepts in the most promising direction. This approach is in contrast with design methods in which the designer makes great efforts to develop a number of alternatives in depth (e.g., Ullman 2010), and at the end of the process applies a traditional evaluation method such as Pugh's (1991) to choose the best concept. However, convergent thinking concerning structural attributes is not a hard rule. There are certainly cases where the degree of innovation, the development risks and the level of uncertainty are so high, that two (or more) alternative ideational solutions are developed in parallel, realized in depth with structural attributes, sometimes up to the stage of prototype production, and the best concept is chosen at the end of the process.
- Divergent thinking about ideational attributes and convergent thinking concerning structural attributes seem more effective in terms of time, effort and the potential for innovation. This strategy is in agreement with the Branch and Bound search algorithms (Hillier and Lieberman 2005; Kroll and Weisbrod 2015), which take the best path in order to reduce the number of possible searches. Branch is analogous to diverging

with a variety of alternative ideational solutions and bound is analogous to converging to the most promising concept of the moment for in-depth refinement and realization with structural attributes.

- In practice, designers often think informally and rapidly of several alternatives and select the most promising one for further development. Our model formalizes this way of thinking so that a variety of alternative ideational solutions is generated explicitly.
- Fricke (1996) examined protocol studies of engineering designers and found that both generating only one or very few alternative solutions and generating a large number of different solutions resulted in poor designs. The first approach caused fixation on one solution too early, while in the second, too much time was spent organizing and managing the alternatives rather than focusing on their effective evaluation and modification. Fricke identified successful designers to be those conducting a balanced search for alternative solutions. This balanced, effective procedure is implemented in our model as divergent thinking concerning ideational attributes and convergent thinking concerning structural attributes.
- Shah and Noe (2003) claim that an approach that generates more ideas increases the chance of better ideas. Directing the designer to generate a variety of alternative ideational solutions (divergent thinking regarding ideational attributes), is less demanding in terms of time and effort than full development of multiple solutions, and has a good chance of obtaining a good solution, not just any solution, in terms of creativity and innovation.
- Protocol studies show that most designers form quite early an underlying core concept and keep pursuing it even when faced with implementation difficulties. Rowe (1987) observed that "A dominant influence is exerted by initial design ideas on subsequent problem solving directions …. Even when severe problems are encountered, a considerable effort is made to make the initial idea work, rather than to stand back and adopt a fresh point of departure." Ullman and Dietterich (1987) found that "designers typically pursue only a single design proposal… there were many cases where major problems had been identified in a proposal and yet the designer preferred to apply patches rather than to reject the proposal outright and develop a better one." A similar observation was made by Ball et al. (1994), who attributed this behavior to fixation on early core concept. A prescriptive model that allows a dynamic and flexible process, and assimilates new insights and knowledge created during the process (which may sometimes contradict or not match earlier concepts), seems to increase the likelihood of avoiding fixation on early concepts. This has been implemented in our model by a combination of divergent thinking concerning ideational attributes and convergent thinking concerning structural attributes.

### 3.5 Design spaces

Woodbury and Burrow (2006) claim that design representations are "… invariants of the exploration view and are necessary properties of a useful design space representation." Many "spaces" appear in the design theory literature: customer space, function space, physical space, process space, problem space, solution space, structure space, behavior space, search space, idea space, concept space, and more (Suh 1990; Maher 2001; Dorst and Cross 2001; Bracha and Reich 2003; Weber 2005; Gero and Kannengiesser 2004; Goldschmidt 2014; Marques et al. 2014). Design in the PA method is performed by back-and-forth movement between two spaces: the concept and configuration spaces. C–K theory's design is an ongoing interplay between the concept (C) and knowledge (K) spaces. In general, it seems that many design models distinguish between two spaces: the space where the need, goals, requirements, and design task are defined—the problem space—and the space where the designer generates or searches for a possible solution—the solution space. This is explicit in Maher's co-evolution model, and implicit in Suh's axiomatic design, where the customer and functional spaces are analogous to the problem space and the physical and process spaces are equivalent to the solution space. Similarly, in Gero and Kannengiesser's FBS model, the function and behavior spaces correspond to the problem space and the structure spaces is analogous to the solution space; in Bracha and Reich's coupled design process (CDP), the function space is similar to the problem space and the structure space is equivalent to the solution space. In PA, the movements between the concept space and the configuration space—alternating between realization and abstraction—occur after the customer needs and requirements have been analyzed and converted to a set of engineering requirements. This makes both the concept and configuration spaces comparable to the solution space.

In most models, there is no explicit distinction between the abstract level, that is, the ideational attributes behind the design solution, and the level of hardware representation, i.e., the structural attributes. PA seems to be the only one which explicitly distinguishes between these two levels through its concept and configuration spaces. C–K theory stands out as a descriptive model that defines the design spaces in terms of logical status and not in terms of object state or type. This is a significant difference concerning

what is a concept and what is the intention to design. The relevant spaces in our model follow C–K theory while integrating PA spaces into them.

The new model comprises two design spaces: a concept space and a knowledge space. In the C-space of C–K, we included both PA spaces, such that in our framework the concept space explicitly represents the evolving concept in terms of both ideational and structural attributes. The concept space develops as a tree structure and is used as the "intention to design" (Hatchuel and Weil 2002), or in other words, it is the "fuel" that drives the design process. Additionally, it is used as a representation, documentation, and reflection of the ideational and structural attributes that are generated during the design process; a sort of "bookkeeping" mechanism of the evolving concept. This makes the concept space in the new model analogous to a solution space.

PA does not explicitly represent the knowledge used in design, although knowledge is extensively used and generated by it as in any design process. This means that the design activities, or the reasoning process, take place within the knowledge space, so that the ideational and structural attributes that are generated during the design process come from the knowledge space. The knowledge space can be characterized by two dimensions: the type of knowledge and the mode of knowledge expansion. The type of knowledge refers to knowledge required and used during the design process: general, domain-specific and procedural knowledge (adapted from Ullman and Dietterich 1987; Culley 2014). Briefly, general knowledge refers to knowledge represented by existing data (i.e., information), education, and ongoing experience with different design tasks and engineering disciplines; domain-specific knowledge refers to knowledge that is required for the specific design task; and procedural knowledge refers to knowledge about how to undertake the design process in order to generate a solution, i.e., the problem-solving methodology. Our model includes three modes of knowledge expansion: initial, ongoing and final, as follows:

- Initial knowledge expansion—a stage of need analysis (using tools such as House of Quality or others) involves translating the customer's need (the initial knowledge) into a set of more elaborate, precise, and quantitative engineering descriptions of what the product should do and how well it should do it. The outcome—the added knowledge—is an initial, sometimes ill-defined, design task statement, and engineering requirements list and subsequently, generation of $C_0$ in the concept space.
- Ongoing knowledge expansion—once the designer has set up $C_0$, the starting point in the concept space, an iterative design exploration begins. Each cycle is accompanied by searching for new knowledge (using general, domain-specific, and procedural knowledge), so there is an ongoing process of knowledge expansion, where new knowledge about the evolving concept is added to existing knowledge (K → K in C–K terms). The trigger for knowledge expansion comes from concept exploration. Subsequently, the added new knowledge is used to expand or include the concept tree by adding or subtracting ideational or structural attribute(s) to the evolving concept. This process continues until the designer reaches a satisfactory conceptual solution.
- Final knowledge expansion—before the process continues to detail design, the design task, and requirements should be finalized and become well understood and defined. The final concept, as well as the knowledge generated during the ongoing knowledge expansion, i.e., new and sometimes unexpected evaluation criteria and design aspects, is used to refine the scope of the design task and the engineering requirements to a final and well-defined state.

### 3.6 Design operators

The design operators for moving within and between the design spaces are a combination of synthesis (of ideational or structural attributes) and evaluation, with "oscillations" between them. The synthesis activity is defined by two types of operators: ideational synthesis (IS) and structural synthesis (SS). The task of the IS operation is to generate new or improved concepts by adding new ideational attributes and sometimes subtracting existing attributes (ideational and structural). The task of the SS operation is to realize the new ideational attributes with new specific structural attributes, and move the design process from the ideational level into the structural or configurational level.

While both synthesis operators produce new entities, their application is controlled by evaluation steps. The new model incorporates three types of evaluation operators (E), defined as follows:

- E type I—To facilitate the design exploration strategy of steepest-first, E type I is an activity in which the designer evaluates all the design aspects and chooses to focus first on the most difficult and challenging aspect(s) of the task. E type I is applied only to $C_0$.
- E type II—To expedite the design exploration strategy of convergent thinking regarding structural attributes, E type II is an activity of selection whose purpose is to narrow down optional solution paths. The designer determines which of the alternative ideational solutions has a better chance of resulting in a successful solution and (at least temporarily) pursues that path. Having in mind only a

general description of the ideational solutions, E type II is performed by cursory comparative evaluation, perhaps by reviewing the pros and cons of each alternative using general and qualitative criteria such as ease of achieving low weight, availability of technological capabilities, robustness, simplicity, and cost.

- E type III—This is a type of analysis, and can be applied to concepts that already have some structural attributes (i.e., configurations represented as sketches, CAD models, important dimensions, and material properties, etc.) The main objectives of E type III, and respectively, the added new knowledge that this operator generates, are to (1) provide quantitative insights about the performance and behavior of the evolving solution; (2) reveal weaknesses, new critical design issues and contradictions (technical and physical) that cause non-compliance with the requirements or otherwise render the solution unfeasible; (3) discover new evaluation criteria that should be applied together with the existing ones, and are part of the refinement process that brings the engineering requirements from being initial and ill-defined to final and well-defined; and (4) make a decision on how to proceed.

Many analysis, modeling and simulation approaches can be used in E type III; for example, TRIZ (Altshuller 1984) for identification of contradictions and the dimensional analysis conceptual modeling (DACM) framework (Coatanéa et al. 2016) from systems engineering. One of the aspects handled by this evaluation activity is avoiding conflicts and checking compatibility among the solutions of the various functions in $C_0$.

E type III includes making one of the following decisions regarding the continuation of the design process:

1. Decision 1—If the concept's behavior is as desired and nothing is missing, then stop the process, meaning that the conceptual solution is complete.
2. Decision 2—If an undesired behavior is detected or something is still missing in the concept, but its value is still considered to be the highest among all the other existing concepts—that is, there is a chance that the undesired behavior can be fixed—then try to improve the current path by adding new ideational attributes and sometimes subtracting existing ideational and structural attributes to/from the latest concept.
3. Decision 3—If the undesired behavior results from critical issues that seem unsolvable, then stop the current path, subtract existing ideational and structural attributes, and backtrack to an existing but unexplored path, i.e., to an alternative ideational solutions from previous steps, which had not been selected earlier for in-depth refinement and realization with structural attributes.
4. Decision 4—If the value of all existing concepts is very low, then stop the current path, subtract existing ideational and structural attributes, and backtrack to an unknown path, i.e., a totally different or new solution direction that had not been considered earlier.
5. Decision 5—If the value of all existing concepts is very low, and there is no new solution direction, then the validity of the root concept, $C_0$, itself should be re-examined and perhaps modified to a new, more general root concept, $C_0^{'}$. This is called "de-partitioning" in C–K terms and has been demonstrated in Kroll et al. (2014).

Decision 1 is the stopping condition for the process, while decision 2 maintains a "linear" path of developing a solution. Decisions 3, 4, and 5 represent backtracking possibilities that provide the designer with the flexibility required of a "real-life" dynamic design process.

### 3.7 Summary of the ICE model

Figure 3 is a schematic of the new prescriptive model. The design process begins with need analysis so that the customer's needs and requirements—the initial knowledge—is expanded to produce the initial and sometimes ill-defined task statement and engineering requirements. Next, the first concept $C_0$ is generated in the concept space and constitutes the root node of the concept tree (C–K's disjunction).

The design exploration moves forward by $C_0$ activating the ongoing knowledge expansion. According to the steepest-first strategy, and based on general and domain-specific knowledge, the E type I evaluation operator is used to decide on the most difficult and challenging aspect(s) of the design task, those that make the task a concept relative to the existing knowledge (C–K's K-relativity). Next, by applying the ideational synthesis (IS) operator and in compliance with the design strategy of divergent thinking about ideational attributes, several alternative ideational solutions, i.e., concepts of how to implement the most difficult and challenging aspect(s) of $C_0$, are generated. The concepts are expressed by groups of ideational attributes and in effect expand the concept space.

The second step of the ongoing knowledge expansion consists of generating structural attributes. To facilitate the design exploration strategy of convergent thinking regarding structural attributes, E type II evaluation is applied to determine which of the potential concepts has a better chance of resulting in a successful solution (this concept is sometimes referred to as having the highest value among all the concepts). The selected concept is next realized by applying the structural synthesis (SS) operator, resulting in a new concept whose meaning is that the ideational attributes are now realized with the specific structural attributes.

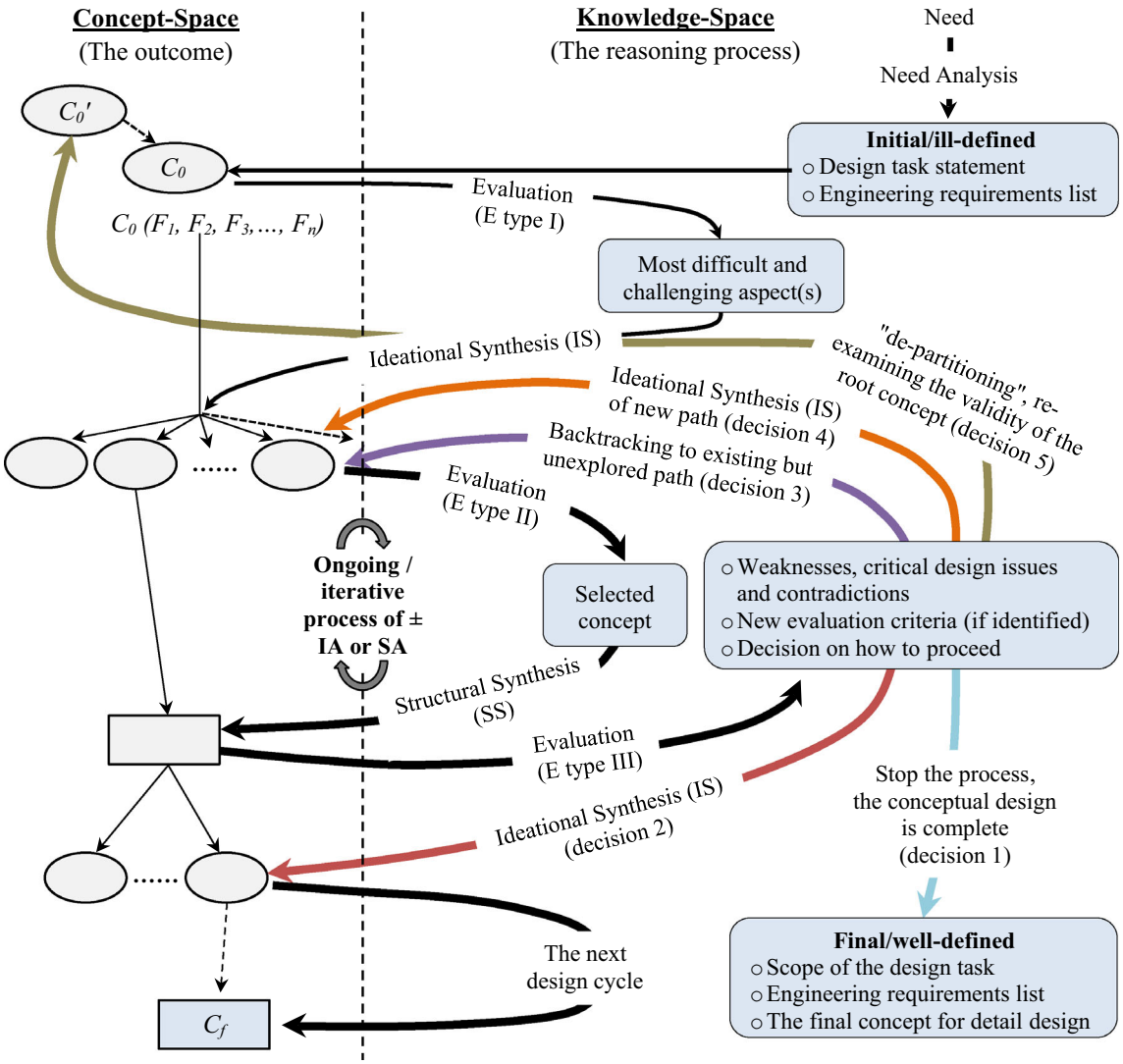



**Fig. 3** The ICE model. *Ellipses* denote concepts generated by adding new ideational attribute(s) and sometimes subtracting existing attribute(s) (ideational or structural). *Square boxes* denote concepts realized with added specific structural attribute(s). *Bold arrows* denote ongoing/iterative processes

The third step of the ongoing knowledge expansion consists of a quantitative performance evaluation. By applying the E type III evaluation operator and using general and domain-specific knowledge to carry out approximate calculations and assessments, the designer evaluates the behavior of the evolving concept and accordingly makes a decision on how to proceed. If the design is still incomplete, a new cycle of design exploration begins according to one of the decisions 2, 3, 4, or 5.

All in all, moving the design process from the ideational level (ellipses in the concept space of Fig. 3) to the structural or configurational level (square boxes) is done by applying an E type II evaluation operator plus structural synthesis (SS). Moving from the structural level back to the ideational one is done by applying an E type III evaluation plus ideational synthesis (IS) operators (in the case of decisions 2–5).

This iterative process takes place until the designer reaches a satisfactory conceptual solution. Once a conceptual solution to the most difficult and challenging aspect(s) of $C_0$ has been finalized, the designer should deal with the other, easier aspects, by repeating the process and of course maintaining compatibility with previously generated solutions. When a final concept has been reached, covering all aspects of $C_0$, the design exploration stops (C–K's conjunction), and a final knowledge expansion takes place whereby the design task and requirements are finalized and become well understood and defined.

## 4 Demonstration

The following is a real design task that originated in the defense industry.

### 4.1 Problem description

Today, most combat ships are equipped with electronic warfare systems and radar counter measures (RCM) in order to protect themselves against threats such as radar-guided missiles. The RCM is activated when an attack is either expected or detected. The basic idea is that the ship under attack creates an illusion of a radar image at a certain distance from the ship. The expected outcome is that the missile will be guided towards the decoy. Figure 4 schematically illustrates the deployment of a radar decoy: an airborne vehicle is launched from a ship and fired into a trajectory. It is propelled by a rocket motor or launched by a piece of artillery. At a given point on the trajectory, and initiated by self-timing, the folded radar decoy is ejected from the airborne vehicle and deploys to become operative.

Most existing RCM decoys are based on chaff. However, modern radar-guided missiles are capable of ignoring the chaff, so defeating these threats require a different physical principle. An effective solution is based on a corner reflector, which returns a signal with similar characteristics to the real target. Corner reflectors, as shown schematically in Fig. 5, consist of three mutually perpendicular, intersecting flat surfaces that reflect the radio waves directly back towards the source. The corner reflector surfaces should be made from conductive material.

### 4.2 Conceptual design using the ICE model

The focus in this demonstration is on the RCM, therefore the list of requirements relates only to limited aspects of the entire problem. In addition, in the above design task, part of the solution to create a realistic radar image was actually defined by the customer, i.e., a solution that should be based on the principle of a corner reflector, and not chaff or another alternative. However, no particular solution for implementing it was defined.

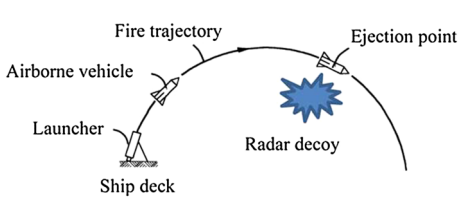



**Fig. 4** Schematic description of deploying a radar decoy

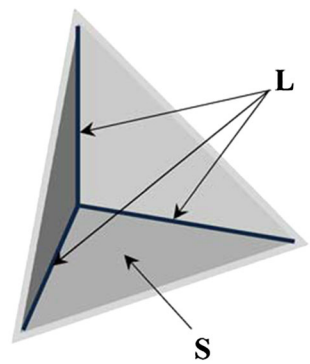



**Fig. 5** A corner reflector (one *trihedral* shown). *S* surface, *L* length

#### *4.2.1 The initial knowledge expansion*

The design process begins with need analysis so that the customer's need is analyzed. Consequently, the design task statement is formulated as developing an RCM that is based on the principle of a corner reflector. The deployment method is required to remain as in the process described in Fig. 4. Next, a list of initial engineering requirements is generated as follows (only a partial list is presented):

1. The radar decoy should have eight back-to-back trihedral corner reflectors.
2. The airborne vehicle chamber is required to have a maximum diameter of 130 mm and length of 750 mm (compatible with standard/existing launchers).
3. The required deployment altitude is about 500 m above sea level.
4. The required deployment distance from the ship is between $d_1$ and $d_2$ m (actual numbers are confidential).
5. The decoy should stay in the air for at least 60 s.
6. The maximum deployment time (to be operative) should be 2 s.
7. The maximum payload mass (the decoy) is 15 kg.
8. The length ($L$) of each side of the trihedral corner reflector should be at least 1 m.
9. The decoy surfaces must be perpendicular to each other with a maximum deviation of $\pm 3°$.
10. Each decoy's surface, $S$, is allowed to have a maximum deflection of 5 mm.
11. The corner reflector surfaces must be made of a reflective material that can be folded into the airborne vehicle chamber.
12. The required reliability of the solution is such that it will deploy properly after being packed in the folded state for a long time.

Next, according to the definition of the first concept, $C_0$ is generated in the concept space, so that $C_0(F_1, F_2, F_3, F_4)$ is defined by the following four basic functions:

$F_1$—Launch an airborne vehicle from a ship launcher.

$F_2$—Fly along a given trajectory.

$F_3$—Eject a decoy at a given point on the trajectory.

$F_4$—Create an illusion of a realistic radar image by a corner reflector.

At this stage, the initial knowledge expansion is complete, as shown in Fig. 6.

### 4.2.2 The ongoing knowledge expansion

Step#1—The design exploration moves forward so that $C_0$ is used to activate the ongoing knowledge expansion. According to the steepest-first strategy, and based on general and domain-specific knowledge, the E type I evaluation operator is applied and $F_4$ identified as the most difficult and challenging aspect in relation to the other functions ($F_1$, $F_2$, and $F_3$), for which solutions are basically known and in this particular case do not require innovative design. In fact, $F_4$ is the design aspect that makes $C_0$ a concept relative to the existing knowledge due to the challenge of generating a realistic radar image which is based on the corner reflector. Next, by applying the ideational synthesis (IS) operator and according to the design strategy of divergent thinking concerning ideational attributes, four alternative ideational solutions—concepts of how to implement $F_4$ of $C_0$—are generated. The concepts are expressed by groups of ideational attributes ($IA_i$), and actually expand the concept space. The reasoning process and the outcome of step#1 are shown in Fig. 7.

Step#2—The second step of the ongoing knowledge expansion consists of the first generation of structural attributes. Following the design exploration strategy of convergent thinking concerning structural attributes, and by applying the E type II evaluation operator, concept $C_1$ is selected to be first for in-depth refinement and realization with structural attributes. The evaluation at this step is made by reviewing some pros and cons of each potential concept ($C_1$–$C_4$) using general and domain-specific qualitative criteria. Having in mind only a crude description of each concept, $C_3$ seems the most complicated and least reliable solution, while $C_1$ and $C_2$ are seen as having the potential to be simpler (have fewer components), less costly, and more reliable, with $C_4$ being somewhere in between. Hence, concept $C_1$ is valued higher relative to the other concepts, that is, $V(C_1) > V(C_2) > V(C_4) > V(C_3)$. Concept $C_1$ is next realized by applying the structural synthesis (SS) operator, using general and domain-specific knowledge, resulting in concept $C_5$ whose meaning is that the ideational attributes of concept $C_1$ are now realized with added specific structural attributes. The reasoning process and the outcome of step#2 are shown in Fig. 8.

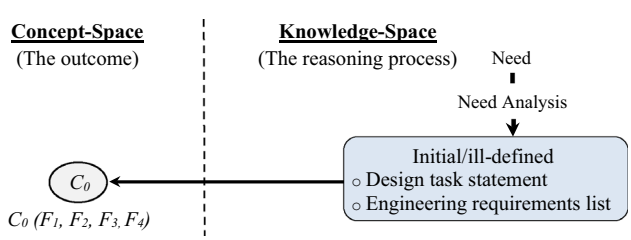



**Fig. 6** The initial knowledge expansion and the subsequent generation of $C_0$ in the concept space

Step#3—The third step of the ongoing knowledge expansion comprises the first quantitative performance evaluation. By applying the E type III evaluation operator, using general and domain-specific knowledge, and making approximate calculations and assessments, the behavior of concept $C_5$ shows that (1) the total foam weight is about 35 kg, i.e., non-compliance with requirement #7, (2) the time in the air is about 39 s, i.e., non-compliance with requirement #5, (3) the compression capability is about 40%, which means that there is non-compliance with requirements #2 and 11, i.e., folding into small dimensions of $\phi 130 \times 750$ mm, and (4) a typical compression set of foams is about 10%, which means that the structure will not deploy to the fully expanded position after being packed in the folded state for a long time, i.e., non-compliance with requirement #12. Based on these findings, which involve critical issues that seem unsolvable, it is decided (decision 3) to stop the current path (concept $C_1$ followed by $C_5$), subtract existing ideational and structural attributes $IA_1$, $IA_2$, $SA_1$, $SA_2$, $SA_3$, $SA_4$, and backtrack to an existing but unexplored path starting with ideational concepts $C_2$, $C_3$, and $C_4$. The reasoning process and the outcome of step#3 are shown in Fig. 9.

Step#4—The fourth step of the ongoing knowledge expansion is the second generation of concepts for which the ideational attributes are realized with added specific structural attributes. Based on the previous E type II evaluation, which was made in step#2, and according to the exploration strategy of convergent thinking concerning structural attributes, concept $C_2$ is selected for further refinement and realization with structural attributes. By applying the structural synthesis (SS) operator, using general and domain-specific knowledge such as design of parachutes, concept $C_2$ is now realized with specific structural attributes, resulting in concept $C_6$ as shown in Fig. 10.

Step#5—The fifth step of the ongoing knowledge expansion constitutes the second quantitative performance evaluation. By applying the E type III evaluation operator, using general and domain-specific knowledge, and making approximate calculations and assessments together with more precise engineering tools, such as computational fluid dynamics (CFD) simulation, the performance behavior of concept $C_6$ shows that (1) the total weight is about 15 kg,

| Step# | 1 |
|---|---|
| The input to the knowledge space | Concept $C_0$ |
| The reasoning process (and respective new knowledge) | Evaluation (E type I ) → Most difficult and challenging aspect (s) → $F_4$ |
| | Ideational Synthesis (IS) → $C_1$ *to* $C_4$, such that:<br>Concept $C_1$<br>$IA_1$ - Shape eight trihedral corner reflectors from flexible foam.<br>$IA_2$ -The flexible foam will be coated with flexible and conductive material.<br>Concept $C_2$<br>$IA_3$ - Shape eight trihedral corner reflectors from flexible conductive material.<br>$IA_4$ - The flexible conductive material will be placed inside the inflated canopy of a descending parachute.<br>$IA_5$ - The decoy will be deployed by the forces generated by the parachute's opening.<br>Concept $C_3$<br>$IA_3$ (existing ideational attribute) - Shape eight trihedral corner reflectors from flexible conductive material.<br>$IA_6$ - The decoy will be deployed by a collapsible mechanism, similar to the principle of an umbrella.<br>Concept $C_4$<br>$IA_3$ (existing ideational attribute) - Shape eight trihedral corner reflectors from flexible conductive material.<br>$IA_7$ - The decoy surfaces will be deployed by an inflatable structure.<br>$IA_8$ -The inflating device will include a central pressure vessel with helium gas. |
| The input to the concept space | Concepts $C_1, C_2, C_3, C_4$ |

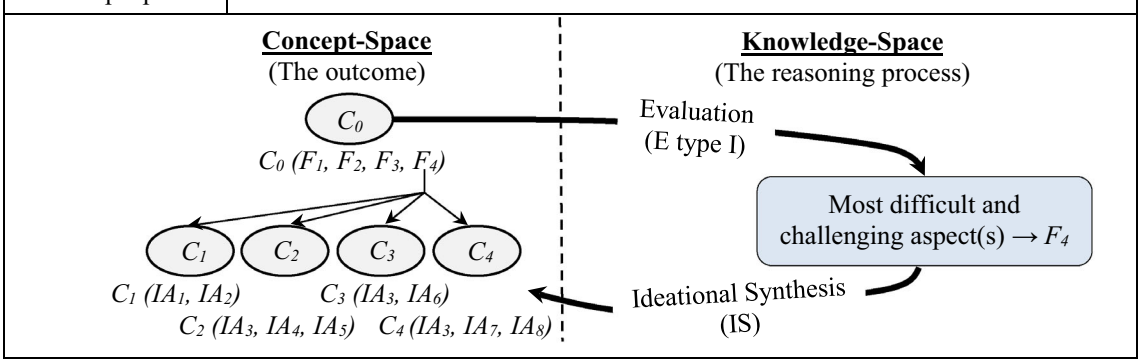
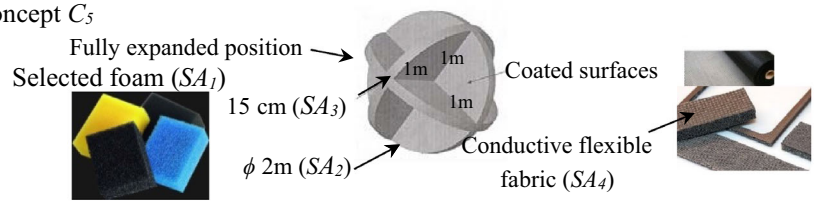



**Fig. 7** The ongoing knowledge expansion, step#1, and the subsequent generation of concepts $C_1$, $C_2$, $C_3$, and $C_4$ in the concept space

i.e., compliance with requirement #7, (2) using the equation of mg = ½ × $\rho$ × $C_d$ × $A$ × $V^2$ (where the mass, $m$, is 15 kg, the air density, $\rho$, is 1.225 kg/m$^3$, the drag coefficient, $C_d$, of a hemispherical parachute is about 1.2, the effective surface area is $A = 3.14$ m$^2$, and the deployment altitude is about 500 m), the total time in the air is calculated to be about 63 s, i.e., compliance with requirement #5, (3) the compression capability is about 80%, which means that there is compliance with requirements #2 and 11, i.e., it folds into small dimensions of ϕ130 × 750 mm, (4) the pure-silver fabric does not suffer deterioration of its radar reflection properties after having been folded, stretched, or pressed together, i.e., compliance with requirement #12, (5) a CFD simulation shows that the incoming flow of air through the horizontal panel into the parachute canopy is insufficient. The result is that the decoy surfaces are not stretched enough and hence there is non-compliance with requirements #9 and 10. Based on these findings, which involve one critical issue, it is decided to try to improve concept $C_6$, i.e., decision 2. By applying the ideational synthesis (IS) operator and following the design strategy of divergent thinking concerning ideational attributes, two alternative ideational solutions (concepts) are generated. The reasoning process and the outcome of step#5 are shown in Fig. 11.

For brevity, the next steps of the ongoing knowledge expansion are not elaborated in detail here. In short, the next step, step#6, is driven by the E type II evaluation plus structural synthesis (SS) operators. Concept $C_7$ is selected (between $C_7$ and $C_8$) for in-depth refinement and

| Step# | 2 |
|---|---|
| The input to the knowledge space | Concepts $C_1$, $C_2$, $C_3$, $C_4$ |
| The reasoning process (and respective new knowledge) | Evaluation (E type II) → Selected concept among $C_1$, $C_2$, $C_3$, $C_4$ → $C_1$ |
| | Structural Synthesis (SS) → $C_5$, such that:<br>Concept $C_5 = C_1 + (SA_1, SA_2, SA_3, SA_4)$<br>$SA_1$ - The foam is made of closed cell polyethylene with an average density of 25 kg/m$^3$<br>$SA_2$ - The outer diameter of the structure is 2 m (so that L=1 m)<br>$SA_3$ - The thickness of the structure is 15 cm (for toughness)<br>$SA_4$ - The foam is coated with conductive flexible fabric with surface resistivity < X ohm (actual number is classified) |
| The input to the concept space | Concept $C_5$<br>  |

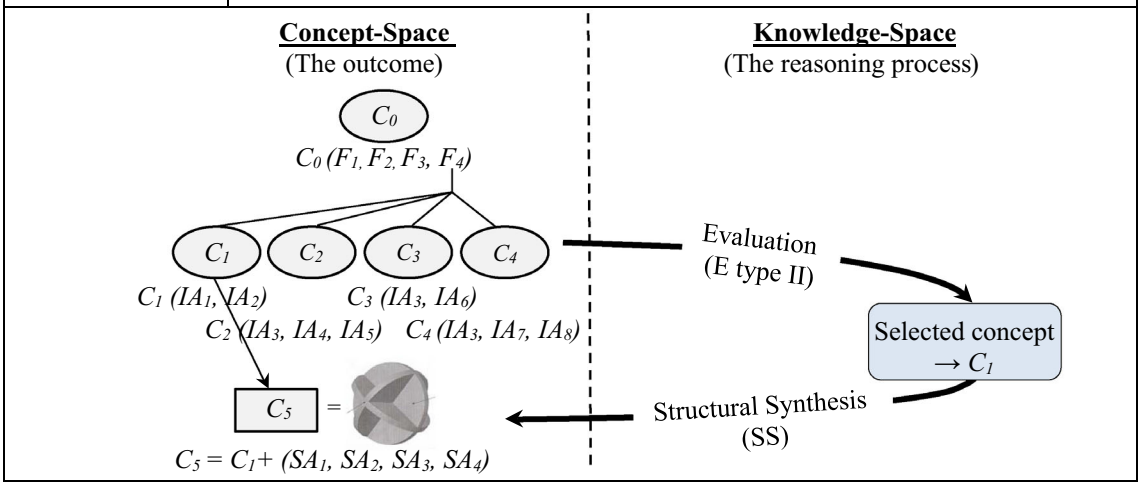



**Fig. 8** The ongoing knowledge expansion, step#2, and the subsequent generation of concept $C_5$ in the concept space

realization with the new structural attributes $SA_{11}$, $SA_{12}$, and $SA_{13}$. The outcome in the concept space, concept $C_9$, is shown in Fig. 12.

Concept $C_9$ is next evaluated by the E type III evaluation operator (step#7). The result shows that concept $C_9$ is not robust in crosswinds (i.e., a new critical issue whose meaning is non-compliance with requirements #9 and 10). Subsequently, a new evaluation criterion emerges (resistance to 15-knot crosswinds). The decision made is to backtrack to concept $C_4$, the inflatable structure (decision 3), keeping $SA_6$ (the reflective material) and continue with the next design cycle. The ongoing knowledge expansion and subsequent generation of new concepts (i.e., the evolution of concept $C_4$) in the concept space progress in accordance with the ICE model and the outcome is that concept $C_4$ eventually becomes a final concept $C_f$, which seems a promising concept in that it satisfies all the requirements. The final concept, as well as the partial concept tree, is shown in Fig. 13.

### *4.2.3 The final knowledge expansion*

Arriving at the final concept, $C_f$ has generated several new and unexpected evaluation criteria and design aspects as a result of the ongoing knowledge expansion. Each of the new design aspects results in new engineering requirements and in fact expands the scope of the design task with significant financial implication in relation to what was understood at the beginning of the design process. For example, the final concept involves development of an inflating device. This design aspect was impossible to identify at the beginning and has been created in response to the specific conceptual solution. The inflating device itself should generate new engineering requirements, such as weight and dimensions of the pressure vessel, gas volume and mass, burst factor, rate of inflation, and more. Hatchuel and Weil (2003) say about such occurrence: “Design does not only transform projects into solutions,

| Step# | 3 |
|---|---|
| The input to the knowledge space | Concept $C_5$ |
| The reasoning process (and respective new knowledge) | Evaluation (E type III) →<br>▪ Performance behavior of concept $C_5$:<br>☒ The total weight is about 35 kg > 15 kg (Req.#7)<br>☒ Time in the air is about 39 sec < 60 sec (Req.#5)<br>☒ Compression capability is only about 40% (Req.#2,11)<br>☒ Does not deploy to fully expanded position after being packed for a long time (Req.#12)<br>▪ Weakness, critical design issues and contradictions → four issues that seem unsolvable.<br>▪ New evaluation criteria → No.<br>▪ Decision on how to proceed → (decision 3) stop the current path, i.e., concepts $C_1$ followed by $C_5$, subtract $IA_1$, $IA_2$ ,$SA_1$ ,$SA_2$ ,$SA_3$, $SA_4$ and backtrack to an existing but unexplored path, i.e., ideational concepts $C_2$, $C_3$, $C_4$. |
| The input to the concept space | Existing but unexplored path, i.e., concepts $C_2$, $C_3$, $C_4$ |

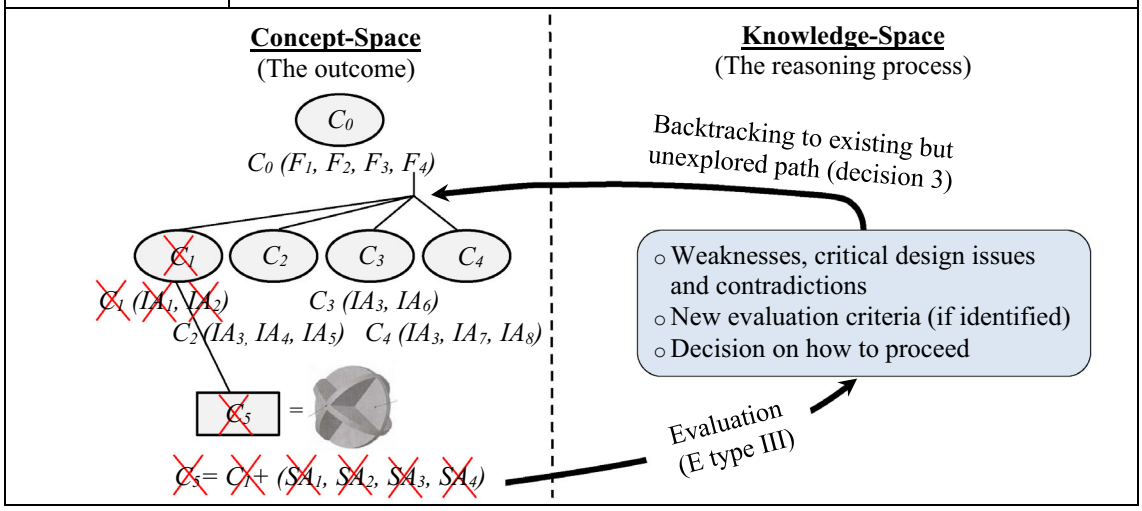



**Fig. 9** The ongoing knowledge expansion, step#3, and subsequently, the subtraction of concepts $C_1$ and $C_5$, and backtracking to existing but unexplored concepts $C_2$, $C_3$, and $C_4$. *Red crosses* symbolize attributes (ideational and structural) and concepts that are subtracted/disqualified after the E type III evaluation (color figure online)

but also projects into projects, or design problems into design problems."

## 5 Discussion

The ICE model uses C–K theory and contributions from other models of the design process to introduce major modifications to the PA method. The model constitutes a prescription for doing conceptual design in a way that is conducive to teaching, learning, and practicing. C–K theory's major contribution to the new model is in providing soundness through the reliance on a well-documented and widely accepted theory. The two spaces from C–K theory, namely the concept space and the knowledge space, are retained in the ICE model to explain its working: C-space contains the evolving solutions, which in turn trigger knowledge expansion in the K-space. The knowledge space is where the design reasoning takes place, and new knowledge allows expansions and inclusions in the C-space, thus facilitating creativity and innovation. While the original distinction made in C–K theory between the spaces based on logical statuses is still valid, the new model gives them a more practical orientation.

A unique characteristic of the new model, originating from PA, is the distinction between ideational and structural attributes of a concept, and accordingly, the division of the synthesis activity into ideational synthesis (IS) and structural synthesis (SS). This feature is useful and effective for the following reasons:

- Similar to the philosophy of brainstorming, which is based on separating the creation stage from the evaluation stage so that "crazy" ideas are welcomed

| Step # | 4 |
|---|---|
| The input to the knowledge space | Concepts $C_2$, $C_3$, $C_4$ |
| The reasoning process (and respective new knowledge) | Evaluation (E type II) → Selected concept among $C_2$, $C_3$, $C_4$ → $C_2$ |
| | Structural Synthesis (SS) → $C_6$, such that:<br>Concept $C_6 = C_2 + (SA_5, SA_6, SA_7, SA_8, SA_9, SA_{10}, SA_{11})$<br>$SA_5$ - The parachute canopy is shaped as a hemisphere with circular inlet diameter of 2 m.<br>$SA_6$ - The decoy surface is made of pure-silver metalized nylon fabric, weighing 40 g/m$^2$, with 47 holes per square inch and resistivity < X ohm.<br>$SA_7$ - Two semi-circular panels (upper) are attached to the interior of the canopy (x-z and y-z planes). Each surface is about 1.57 m$^2$.<br>$SA_8$ - Two panels (lower) are shaped as isosceles triangles (x-z and y-z planes). Each surface is about 1 m$^2$.<br>$SA_9$ - The upper and lower panels are integrated through the horizontal circular panel (x-y plane), which is attached to the canopy, i.e., diameter 2 m. The surface is about 3.14 m$^2$.<br>$SA_{10}$ - The parachute canopy is connected to a 5-kg weight by 21 strings (approximately 5-m long, 2-mm in diameter). |
| The input to the concept space | Concept $C_6$ |

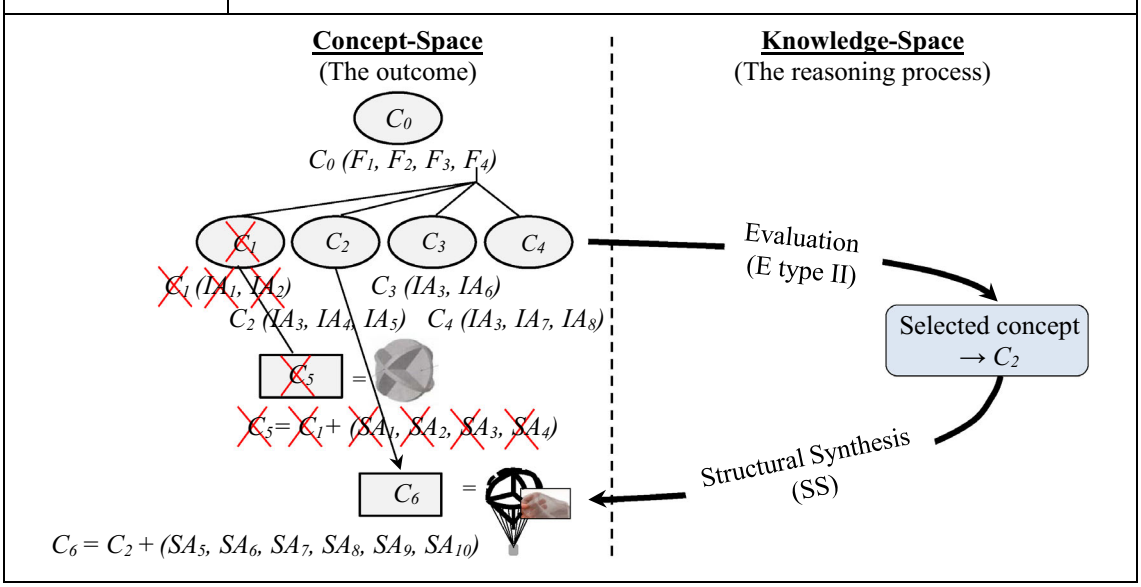



**Fig. 10** The ongoing knowledge expansion, step#4, and the subsequent generation of concept $C_6$ in the concept space

and built upon, the same result can be achieved by distinguishing between the ideational level and the structural or configurational level. This allows the designer to "go wild" and generate unusual solution ideas. At worst, he or she will find out (during the design process, not at the end) that some of the ideational solutions cannot be realized or do not work well.

- From the cost-effectiveness viewpoint, developing a candidate solution in more detail, i.e., representation of

| Step # | 5 |
|---|---|
| The input to the knowledge space | Concept $C_6$ |
| The reasoning process (and respective new knowledge) | Evaluation (E type III) →<br>▪ Performance behavior of concept $C_6$:<br>✓ The total weight is about 15 kg (Req.#7)<br>✓ Time in the air is about 63 sec > 60 sec ( Req.#5)<br>✓ Compression capability is about 80% (Req.#2,11)<br>✓ The pure-silver fabric does not suffer deterioration of its radar reflection properties after having been folded, stretched, or pressed together (Req.#12)<br>☒ Decoy surfaces do not stretch enough (Req.#9,10)<br>▪ Weaknesses, critical design issues and contradictions → the incoming air flow through the horizontal panel into the parachute canopy is insufficient.<br>▪ New evaluation criteria → tension in the canopy.<br>▪ Decision on how to proceed → (decision 2) try to improve concept $C_6$ (whose value is still high). |
| | Ideational Synthesis (IS) → $C_7$, $C_8$, such that:<br>Concept $C_7 = C_6 + (IA_9, IA_{10})$<br>$IA_9$ - Increase the incoming air flow through the horizontal panel by opening a round hole at the top of the canopy and causing a vent effect.<br>$IA_{10}$ - Change the horizontal panel to a square shape, so that space is created between the parachute circumference and the horizontal panel to allow enough air flow.<br>Concept $C_8 = C_6 + (IA_{11}, IA_{12})$<br>$IA_{11}$ - Mechanically increase the tensile forces generated by the parachute.<br>$IA_{12}$ - Add flexible/telescopic rods (similar to the principle of a folding tent) to the canopy. |
| The input to the concept space | Concepts $C_7$, $C_8$ |

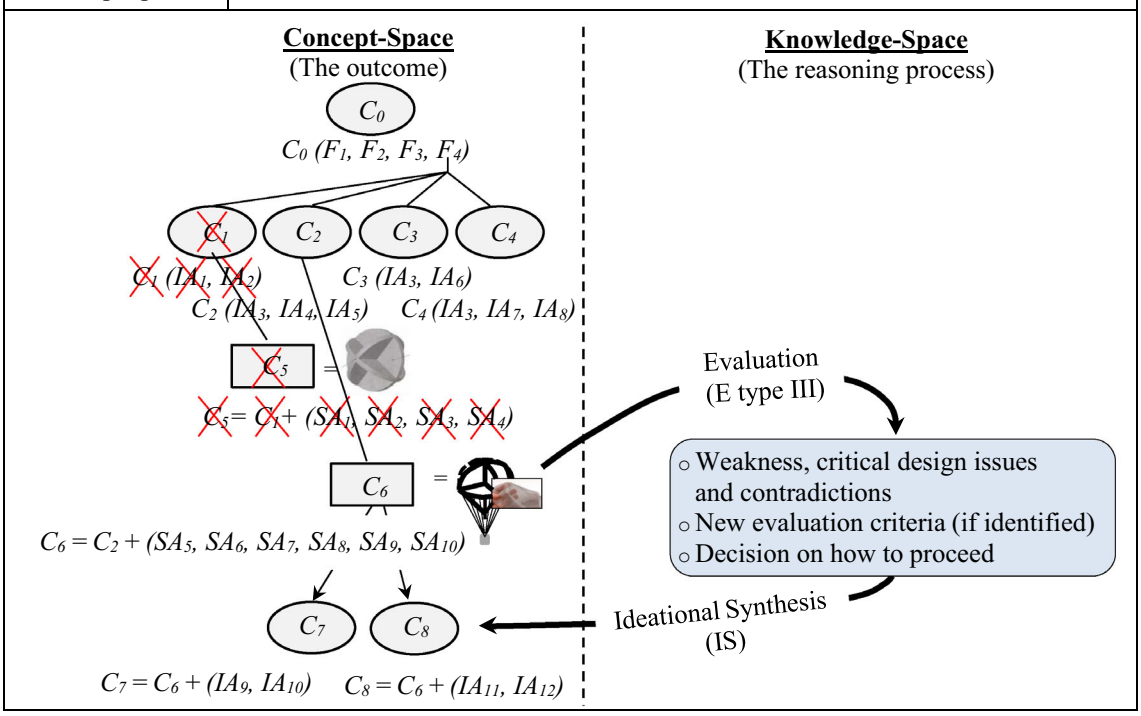



**Fig. 11** The ongoing knowledge expansion, step#5, and the subsequent generation of concepts $C_7$ and $C_8$ in the concept space

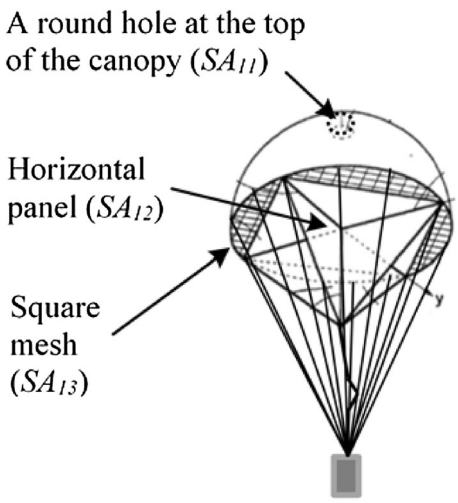



**Fig. 12** Concept $C_9 = C_7 + (SA_{11}, SA_{12}, SA_{13})$; adapted from (Weisbrod 2008)

the hardware, is a design activity that usually requires more time and effort. Therefore, a design process model, which on the one hand allows generating a variety of ideational solutions and on the other hand directs the designer to focus on one high-value solution for hardware description, is likely to be more efficient in terms of resources and increases the probability of the designer exploring original and innovative solutions. A review by Motte (2015) of the effectiveness of using systematic methodologies vs. intuitive approaches offers interesting, but inconclusive, insights related to this point.

- Directing the designer to define the ideational attributes explicitly has the potential to eliminate unnecessary structural features, which in many cases can have significant financial implications, as well as a negative impact on product reliability. In the new model,

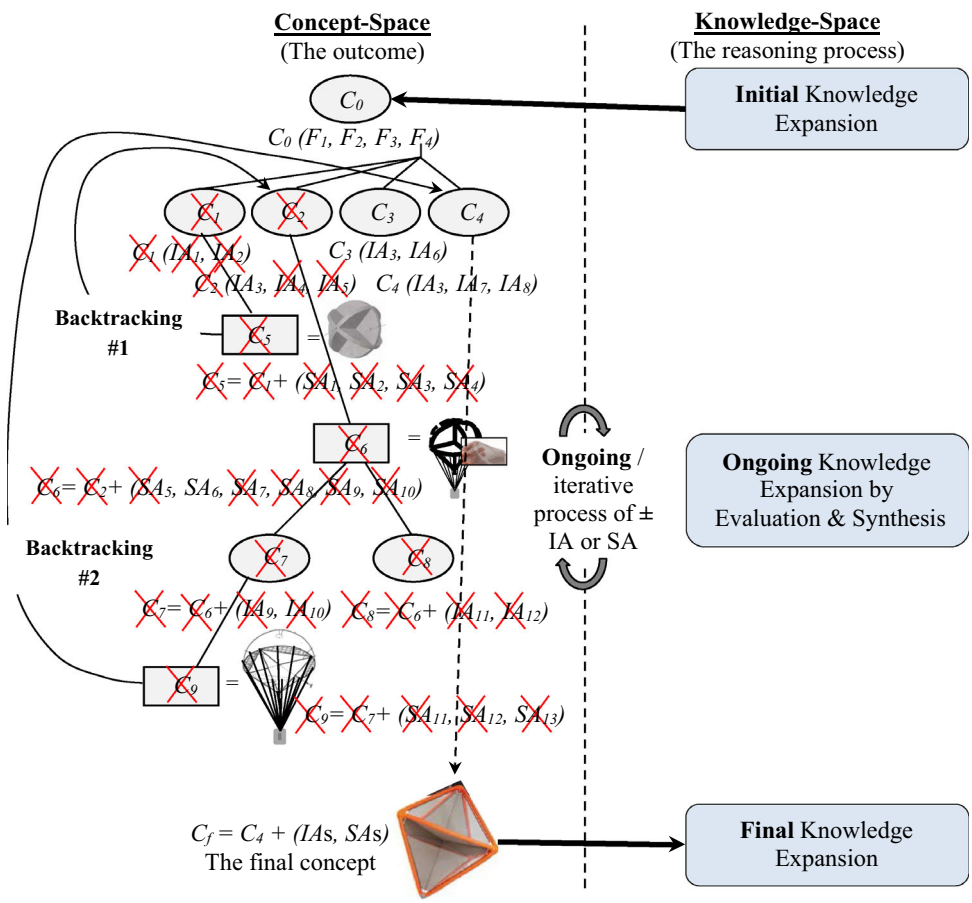



**Fig. 13** The concept tree (not all stages are detailed) and the final concept $C_f$. *Red crosses* symbolize concepts and their ideational and structural attributes that were subtracted/disqualified during the conceptual design process after applying E type III evaluations. *Ellipses* denote concepts generated by adding new ideational attributes and sometimes subtracting existing ones (ideational and structural). *Square boxes* denote concepts realized with added specific structural attributes (color figure online)

structural features can emerge only as realizations of specific ideational attributes.

Further elaboration of the importance and benefits of separating the reasoning in design into solution ideas and their implementation can be found in Kroll and Koskela (2016), who argue that the double mapping, from function to idea and from idea to structure, is a fundamental way of carrying out the function-to-form reasoning in design.

The ICE model maintains the tree-like representation of the evolving solutions from C–K's C-space as a sort of "bookkeeping" mechanism, which is important for the following reasons:

- Regarding human memory limitations, Goldschmidt (2014) defines an internal representation as being generated in mental visual imagery and an external representation as being created in the physical world. She suggests that the main reasons for producing an external representation are to "decrease the load on memory and to assist in explorative thinking." According to Goldschmidt, an external representation such as a sketch "…helps reduce the cognitive load of trying to retrieve and maintain items from long- and short-term memory." These definitions are somewhat similar to our distinction between ideational attributes (Goldschmidt's internal representation) and structural attributes (the external representation), which in our framework are both explicit properties of a concept.
- Experience shows that designers often try to promote their solution and therefore glorify the process without pointing out the difficulties and dead ends along the way. A detailed account of the thought processes and intermediate concepts generated during conceptual design allows capturing the "justifications" and not just descriptions of the final outcome. This need is known as design rationale capture (Kroll and Shihmanter 2011). From the organizational viewpoint, documenting thoughts and concepts can be useful in the long run with respect to different design tasks. Since many designs are redesign, a record of the design process, the decisions that were made and the rationale behind rejected and accepted concepts may be important. Concepts that do not fit a specific problem can often be a good solution to a different problem.

The design operators in the new model were defined by studying PA activities in light of C–K theory. Synthesis and evaluation are the key operators for moving within and between the design spaces. This is consistent with Jones' (1963) model and does not constitute innovation. Kroll et al. (2013, 2014) have already shown that PA's activities (PI, CS, and E, as described in Sect. 1.2) can be modeled as combinations of C–K's operators (C → K, K → C, C → C, and K → K; see Sect. 1.3). The novelty in the ICE model is that different types of synthesis (ideational and structural) and evaluation (type I, II, and III)—to be applied continuously and repeatedly during the conceptual design process—have been defined. The two synthesis operators represent the distinction between generating ideational and structural attributes and implement the desirable exploration strategy of divergent thinking concerning ideational attributes and convergent thinking concerning structural attributes. The evaluation operators also differ in a similar sense: E type I is applied only at the beginning of the process to select the most challenging aspect of the design task, while E type II and type III are applied repeatedly, to ideational and structural solutions respectively, to select the most promising solution path or to analyze the behavior of evolving solutions. Both serve to focus and control the overall progress of the design process in a way that implements the strategy of steepest-first while thinking broadly about ideational solutions and narrowly about structural implementations. The five possible decisions that follow the analysis of E type III have for the first time been formulated explicitly, including a mechanism of backtracking to avoid fixation, thus contributing to the prescriptive nature of the new model while allowing for creativity and innovation.

Overall, the ICE model presents a refinement process in which the design task and engineering requirements are updated from an initial and ill-defined state to a final and well-defined one. The process is solution-focused and not problem-focused, as the latter approach is considered to be less suitable for innovative (Le Masson et al. 2010). Because a good design is a synthesis of a series of good ideas or concepts, not just one good idea, the new model encourages the creation of multiple alternative ideational solutions at each design cycle. And because the design process must eventually converge, evaluation is repeatedly applied so the design process remains focused. The result is a design exploration strategy that we call "steepest-first," emphasizing the handling of the most difficult and challenging issues before moving on to more mundane aspects. It is believed that this approach is how most practitioners work, as opposed to using the breadth-first functional decomposition methods.

## 6 Conclusion and future work

The development of a new prescriptive model for conceptual design, called ICE, has been described and the model demonstrated. It is intended for the generation and development of conceptual design solutions starting from rough ideas all the way to viable embodiments. The model should improve the designer's performance as it captures

the dynamics and rationale of conceptual design. ICE is based on the well-established theoretical foundation of C–K theory and the empirically derived PA method. C–K theory is considered to be a design theory that offers a comprehensive formalization of the design process, independent of any design domain or type of artifact, and describes creativity and innovation within the same framework as the design process. The correctness and effectiveness of the new prescriptive model are strongly based on this accepted theory. Nevertheless, it should be emphasized that C–K theory does not encompass all the activities in design, so stages such as clarifying and analyzing the task to formulate the design requirements and selecting among alternatives, together with some cognitive reasoning steps, were inspired by other design methodologies.

The next stage of this research will be carried out by a second descriptive study, i.e., DS-II in the DRM, as outlined in Sect. 2. The new model will be tested and evaluated in a design experiment by examining the performance of external participants when applying it. However, the preliminary testing and evaluation process actually began during the formulation of the new model. It has been carried out several times by the research team through analyzing a multitude of realistic case studies in an iterative process of testing the model, improving it, testing again, etc. Since the new prescriptive model is strongly based on an accepted theory, i.e., C–K theory, the correctness and consistency come from this theory. The main objectives of the future experimental testing and evaluation are to determine whether the new model can be used as a clear and precise step-by-step procedure, whether it is conducive to teaching and practicing conceptual engineering design, and to see whether it indeed contributes to successful design performance.

To facilitate the experimental evaluation, two categories of success criteria have been planned: applicability of the process and effectiveness of both the process and its outcome. Metrics for assessing the applicability criterion will include the model's conduciveness to teaching, ease of comprehending its key notions, terminology and underlying factors, ease of use in practice, and the degree to which it is followed correctly. Effectiveness will be assessed by the model's contribution to generating a solution that meets the requirement, to creativity and innovation in the process, to a dynamic and flexible process, to identifying weaknesses in evolving solutions and screening alternatives towards moving in promising directions, and to capturing the design rationale. A thorough description of the planning and execution of the experiment, together with an analysis of the results, will be published separately.

**Acknowledgements** This work was supported by the Israel Science Foundation under Grant number 546/12.

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Research in Engineering Design (2020) 31:103–122
https://doi.org/10.1007/s00163-019-00324-6

ORIGINAL PAPER

# Testing and evaluating the applicability and effectiveness of the new idea-configuration-evaluation (ICE) method of conceptual design

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Received: 7 June 2018 / Revised: 18 August 2019 / Accepted: 10 October 2019 / Published online: 22 October 2019


**Abstract**
In a previous paper, we introduced the process of developing a new prescriptive method for conceptual engineering design called ICE (idea-configuration-evaluation), and demonstrated its application in detail. The new design model is based on the well-established theoretical foundation of C–K theory and the empirically derived parameter analysis method. In this paper, we describe the testing and evaluation of the model's formulation through a design experiment that examines the performance of external participants when applying it. Two categories of evaluation metrics are used: applicability and effectiveness of the method. Nine quantitative and qualitative metrics describe aspects such as the ease of teaching and using the design procedure, and its support of creativity and innovation. The experiment took place in an academic environment and the results were obtained by analyzing detailed written design reports, assessing characteristics of the final solutions, and examining replies to reflective questionnaires. The conclusions from the study are that the ICE model presents a clear and concise step-by-step procedure, is conducive to teaching and practicing design, captures the dynamics and rationale of the conceptual design process, and can therefore lead to viable and innovative conceptual designs. Another, general contribution of the paper is in delineating the application of a plurality of measures in a non-comparative assessment of a design method.

**Keywords** Design experiment · Design method evaluation and testing · Conceptual design · Design process model

## 1 Introduction

### 1.1 Motivation and background

A conceptual design method called parameter analysis (PA) taught to engineering students for several decades has recently been combined with the C–K design theory, to form a new prescriptive model of conceptual engineering design named idea-configuration-evaluation (ICE) (Weisbrod and Kroll 2018). This model is based on fundamental notions of PA, such as mentally moving back and forth between the space of ideas and space of configurations, carrying out repeated evaluations, and developing the solution in a steepest-first manner. C–K theory contributed, among others, the understanding of the use of existing and new knowledge during design, the operators involved in the process, and the formal structure of a concept. The resulting new model was designed as a teaching method, so it is formulated as a systematic procedure. It is assumed that after gaining experience in designing with ICE for a while, the practitioner will not need to adhere to this prescriptive model so closely, but will naturally adopt its way of doing design.

Part of the development process of ICE required that the model be tested and evaluated to identify and correct weaknesses, and to assess its usability and suitability as a teaching and learning method in engineering design. The development of ICE followed the design research methodology (DRM) of Blessing and Chakrabarti (2009), as explained in Weisbrod and Kroll (2018), so ICE's testing and evaluation correspond to the DRM's descriptive study-II stage. The testing and evaluating presented here should not be taken as providing proof of scientific validity of the ICE model. Because the new design method is based on the widely accepted C–K theory, the correctness, consistency and effectiveness come from this theory. The theoretical foundation

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is complemented by a sound and rigorous development process, with ongoing evaluation via analysis of realistic design problems as case studies. Therefore, the main objectives of the current experimental testing and evaluation are to determine whether the present realization of the ICE model can be used as a clear and precise step-by-step procedure, whether it is conducive to teaching and practicing conceptual engineering design, and whether it indeed contributes to successful design performance and outcomes. It follows that the research question addressed in this paper is how to test and evaluate a design method. An evaluation procedure developed to test a specific design method should also be applicable to other methods, and to comparative studies of multiple methods.

To further clarify the goal of the present research, the informal definitions of the terms validation and verification from Boehm (1981), p. 37, should be consulted. Validation is checking whether we are building the right product, and verification is checking whether we are building it right. In other words, validation refers to checking fitness against an external goal, and verification deals with the correspondence between a product and its specification.[1] Similarly, Forsberg and Mooz (1999) also distinguish between validation and verification in the famous Vee model of system engineering. Validation refers to confirming fit of the system to the (external) user needs and requirements, while verification is the testing and evaluation against the (internal) specifications created by the designer.

In our case, validation of the ICE model comes from its derivation from PA and C–K theory, as described in Weisbrod and Kroll (2018). Here we address verification: the correlation between the product—the particular formulation of the ICE method—and the goal of being conducive to teaching, learning and applying. Hence, the current effort does not evaluate ICE externally, as fit for the purpose of educating engineering students in the sense of acquiring design skills and capabilities. Rather, it attempts to assess the specific construction of ICE as an applicable and effective teaching method.

To test and evaluate the ICE model, an appropriate experiment needed to be designed, where participants were instructed in using the method, then they put it to practice, and finally their performance was analyzed and evaluated. The evaluation metrics—*what* should be measured—were established early in the study, before developing the new design model itself. They include measures to assess how applicable and effective the method is. Next came the design of the experimental procedure—*how* to measure—consisting of the question whether the experiment should be comparative or not, the setting for the experiment (i.e., industrial or academic), the design task to be assigned to the participants, and techniques for collecting data.

After the short description below of the ICE model, Sect. 2 presents a review of the issues and problems related to the current study, with the pertinent solution approaches found in the literature. The research methodology is described in Sect. 3, with details of the developed comprehensive toolbox of evaluation metrics, and in Sect. 4, with the experimental procedure used in this work. The results and findings are presented in Sect. 5, followed by a discussion in Sect. 6.

### 1.2 Idea-configuration-evaluation (ICE): a brief overview

ICE is based on the well-established theoretical foundation of C–K theory (Hatchuel and Weil 2002, 2003, 2009; Le Masson et al. 2010) and the empirically derived parameter analysis method (Kroll et al. 2001; Kroll 2013; Kroll et al. 2014). A detailed description of its development and a demonstration can be found in Weisbrod and Kroll (2018). Figure 1 is a schematic diagram of the ICE model.

The design process according to ICE begins with need analysis, wherein the customer's needs are studied and converted to a sometimes ill-defined task statement and list of engineering requirements. Next, the first concept $C_0$ is generated in the concept space and constitutes the root node of the concept tree. This completes the stage of initial knowledge expansion.

The design exploration moves forward by $C_0$ activating the ongoing knowledge expansion. According to ICE's steepest-first strategy, the E type I evaluation operator is used to make a decision—based on general and domain-specific knowledge—regarding the most difficult and challenging aspects of the design task, those that make it a 'concept' relative to the existing knowledge (K-relativity in C–K). Next, by applying the ideational synthesis (IS) operator and in compliance with the design strategy of divergent thinking about ideational attributes, several alternative ideational solutions—concepts of how to address the most difficult aspects of $C_0$—are generated. The concepts are expressed as groups of ideational attributes and in effect expand the concept space.

The second step of the ongoing knowledge expansion consists of implementing the ideas as configurations, or hardware representations. To facilitate the design strategy of convergent thinking regarding structural attributes, E type II evaluation is applied to determine which of the potential concepts has a better chance of resulting in a successful solution (that concept is considered to have the highest value among all existing concepts). As the concepts consist of general descriptions only, the evaluation in this step is made

[1] As pointed out by Seepersad et al. (2006), validation and verification are sometimes used with the opposite meaning to this definition.

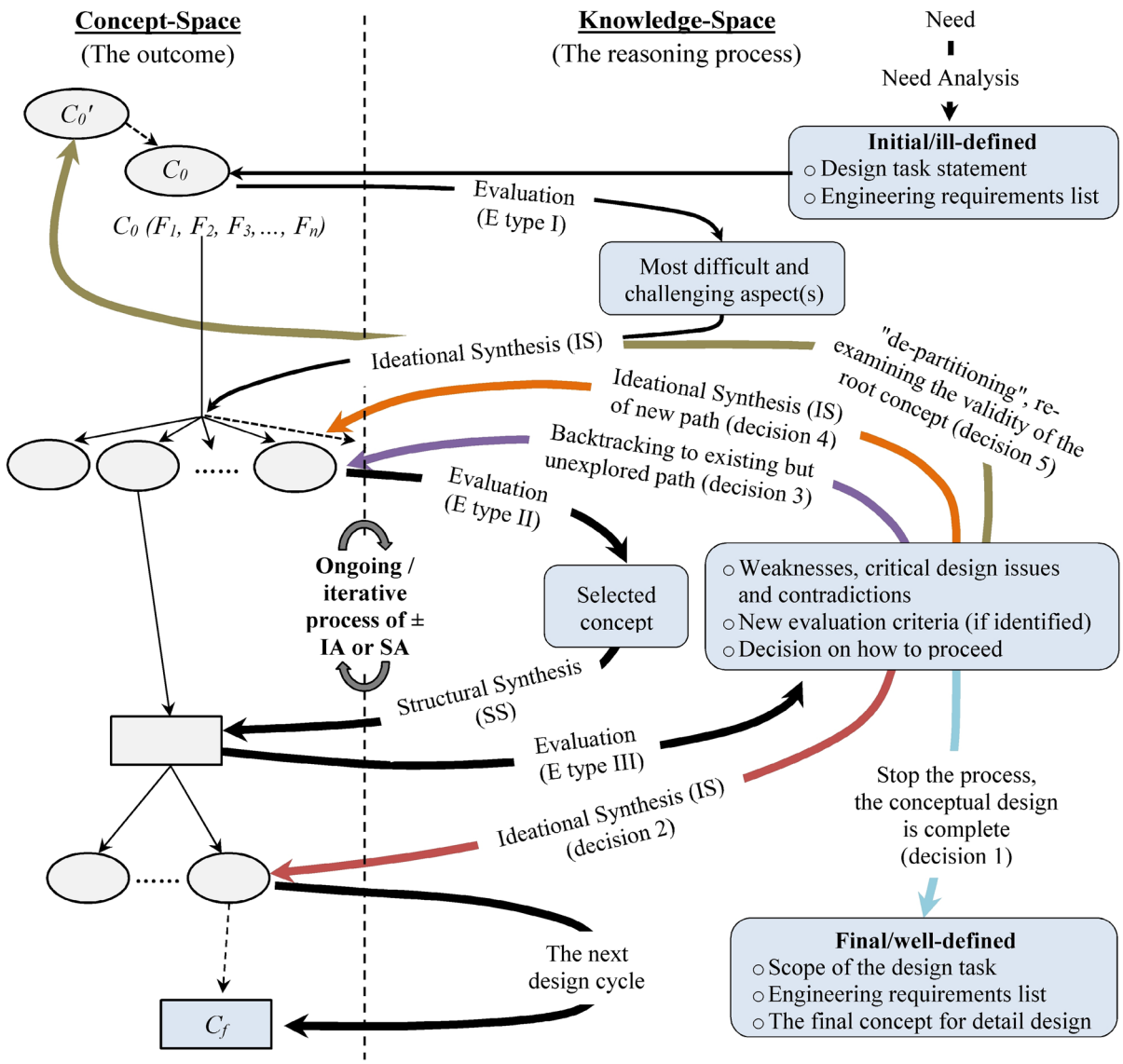


**Fig. 1** The ICE model. Ellipses denote concepts generated by adding new ideational attributes and sometimes subtracting existing attributes (ideational and structural). Rectangles denote concepts realized with added specific structural attributes. Thick arrows denote ongoing iterative processes

by reviewing some pros and cons using broad, qualitative criteria. The selected concept is next realized with specific structural attributes by applying the structural synthesis (SS) operator, resulting in a new concept that is added to the concept tree.

The third step of the ongoing knowledge expansion comprises the first quantitative performance evaluation. The E type III evaluation operator is used for approximate calculations and assessments, so that the designer can evaluate the performance behavior of the evolving concept and accordingly, make a decision on how to proceed. If the design is still incomplete, a new cycle of evolving the design begins along one of decisions 2, 3, 4 or 5 shown in Fig. 1.

This iterative process continues until the designer reaches a satisfactory conceptual solution of the most difficult aspects of $C_0$ and then continues in a similar manner with the other, easier facets. When a final concept has been established, covering all aspects of $C_0$, the design exploration ends and a final knowledge expansion takes place whereby the design task and requirements are finalized and become well understood and defined.

## 2 Problems, solution approaches and related literature

In this section, we outline and discuss some important issues related to testing and evaluating design methods, including the dilemma of whether a comparative experiment should be conducted, the appropriate setting for such an experiment, what design task to assign, how to collect data, and how to assess creativity and innovation. The choices we made for the evaluation metrics and experimental procedure follow in Sects. 3 and 4.

### 2.1 Assessment of design methods

Procedures and metrics for testing scientific models are usually quite clear. In contrast, design research deals with mental processes and human behavior, so the testing and evaluation of a design method are more challenging. For example, it is possible to propose a procedure in which human designers are monitored while doing design and the experimental protocols studied. However, this protocol analysis approach may not indicate clearly what the thought processes are, may affect the design process itself, and may not be applicable to processes whose duration is more than a few hours. A good discussion of the experimental methods in design research, including the case study method, can be found in Hernandez et al. (2010). Strickfaden and Heylighen (2010) list the problems associated with experimental design studies and suggest that a better approach would be to explore how design processes are perceived by design educators, because "…design teachers tend to develop a more articulate view of design processes than most other designers."

Frey and Dym (2006) draw an analogy between validation of design methods and evaluating medical treatments. They propose testing new design methods by applying them to design process models, just as new drugs are tested on animals, and collecting data of the methods' use in industry in a similar manner to clinical trials. Reich (2010) describes some of the issues related to testing and evaluating design methods, including having many variables that cannot be measured accurately, aspects that are not controlled (personal abilities, motivation, experience, etc.), context dependence of the experiments, and poor repeatability.

Vermass (2014) offers a philosophy of science perspective on the issue of testing design methods. He discusses several existing approaches and says that what impedes the effectiveness of the testing is considering it as validation, that is, testing all the claims derivable from the method and attempting to confirm them. Seepersad et al. (2006) suggest that validation of a design method is a process of building confidence in using the method with respect to a specific purpose, and this can be done by the "validation square". First, the constituents of the method should be accepted separately and as a whole; second, example problems should be accepted as representatives of the domain of application of the method; third, successful resolution of the example problems by the method should be shown and attributed to using the method; and fourth, the usefulness of the design method should be accepted by a 'leap of faith' for all the design problems represented by the examples.

Motte and Eriksson (2016) present a detailed framework for assessing methodologies under development, where an encompassing set of characteristics can be used both for driving the development process and as evaluation criteria. Keller and Binz (2009) define a set of 19 requirements in 8 groups that can be used to assess newly developed design methodologies. Among the groups of requirements are usefulness, flexibility and comprehensibility. They further investigate the interdependencies among the requirements, showing that only two requirements are completely independent. Lewis et al. (2011) address a specific class of problems—improving an existing design—and propose metrics for assessing both the quality of the design concepts proposed by the participants and the thought processes—ideation and argument—of the designers.

### 2.2 Comparative experiment: yes or no?

The question of whether an experiment in design, whose purpose is to study the applicability and effectiveness of a newly developed method, should or should not be comparative, is significant. It is tempting to propose a comparative experiment, in which one group (the control) uses a more traditional method while a second group uses the new method. This approach can even be extended to three groups: doing conceptual design without any method at all, using a traditional method, and applying the new method. However, a comparative experiment has several drawbacks and difficulties:

- A comparative experiment means that both models, the old and the new, will have to be taught to the participants so they can use them. A suitable and objective framework for such teaching is difficult to achieve. There is no way to guarantee that the two groups will reach the same level of competency before conducting the experiment, and the instructors may also be biased while teaching the methods.
- The design process deals with mental processes, so the preference of one design method over another can be

a subjective matter that depends on personal habits, organizational culture and different people's conceptions. There is no absolute truth, good or bad here, and a design method that is useful and effective for one person working on a specific problem in a particular setting can be less beneficial and suitable for another person or under different circumstances (Reich 2010).

- Comparative evaluation of different solutions is difficult, and can sometimes be subjective and exposed to different interpretations even if the evaluation is based on predefined metrics. For example, Chulvi et al. (2012) analyzed the influence of three design methods—brainstorming, functional analysis, and SCAMPER—on the degree of creativity of the design outcome. The experiment was carried out by four multidisciplinary teams who were instructed to solve four different design problems. Different problems and design methods (including no method) were assigned to each team in each session. The argument for this approach was to minimize noise factors, such as the differences among the participants, the problems and the methods used. To evaluate the degree of creativity of the design outcome, they used three different metrics—metric of Moss, metric of Sarkar and Chakrabarti (see Sect. 2.6) and evaluation of innovative potential—as well as evaluation by experts of the degree of novelty, usefulness and creativity of the solutions. The experts' opinions presented significant disagreements in relation to the evaluation conducted by the researchers using the three metrics. One expert had to be excluded from the study because the deviation of his answers was higher than three standard deviations. This example shows the difficulty of quantitatively evaluating conceptual solutions due to subjectivity. This, of course, is a problem with any design experiment, but may have a higher negative significance in a comparative study.

Even if a comparative experiment could be performed without any limitations and difficulties, it would defy our main objective. We do not claim that our design method is better than others, but rather, attempt to assess the value of a particular conceptual design method, ICE, when taught, learned and used. For this reason, we cannot base our evaluation only on final outcomes—the designed artifacts. Rather, we need to analyze the design process itself, and in particular, the extent to which it has been followed correctly. This in turn requires that detailed records of the thought processes and incremental evolution of the designs be created. A comparative study would have involved a large variety of processes, with high likelihood for questionable analysis results.

By choosing the non-comparative option, then even in cases where the designer does not present a high quality and viable conceptual result, analysis of the design process can contribute substantially to understanding the strengths and weaknesses of the model. According to the results obtained, possible improvements can be incorporated in the method itself, and the way we teach it. Of course, the designed artifacts themselves will also be included in the evaluation.

### 2.3 Experimental environment and participants: industrial or academic?

Testing a new design method in an industrial environment, with a real design task and over a relatively long time, has a clear advantage. The results would relate to a real-life context: a genuine situation with authentic consequences if the task were not carried out properly. The design process would have to be executed in accordance with all the "rules" and formal steps with no shortcuts; a variety of design tools and resources such as CAD software, simulations and prototyping would be available. Project management considerations and constraints would come into play. However, industrial testing also has drawbacks: (1) it is rarely possible to examine real design projects generated in industry because of classification constraints, business sensitivity and time investment required from the designers; (2) the research activities may be difficult to plan as the researcher has no control over the process that can take a long time and there is no guarantee that the design process will continue without interruption (Blessing and Chakrabarti 2009); (3) designers tend to "sell" the product and glorify their process without pointing out the difficulties and dead ends encountered on the way; (4) a long data collection period may distort the conclusions because the designers usually report their thoughts in hindsight, and this may introduce inaccuracies.

Consequently, it was decided that an experiment aimed to evaluate a new design method for the first time should be carried out in an "academic laboratory" environment. This may seem contrary to the accepted practice in qualitative research in social studies, where the research is executed in the participants' natural environment, but was deemed necessary due to the difficulties and limitations as described above. Of course, an academic experiment has its limitations, and those will be discussed in Sect. 6. Once more experience has been gained with the new model, it will be beneficial to implement it in an industrial environment, with a real design task, because continuous evaluation over time, including incremental improvements, is an integral part of the evolution of a new design method.

### 2.4 The design task

In choosing a design task for an experiment on a new design method, several aspects or criteria need to be considered. The novelty and uniqueness of the design task should entail creativity and innovation to solve it, not just searching for existing or similar solutions. It is advisable to select

a non-trivial and "open" problem, one whose solution is challenging enough to result in an interesting design process. The task should deal with diverse engineering dilemmas and design aspects, require examination and evaluation of alternative solutions and implementation of several design cycles. The design task should be matched to the participants' background so that they possess the knowledge required to solve it. Realistic design tasks are often interdisciplinary and therefore require knowledge in diverse engineering fields, so a suitable compromise must be reached. It is also advisable to select an interesting and realistic design task with a real need, for motivational purposes. However, a realistic design task may not fit the criteria and goals of the experiment, so a careful examination of the task is needed, and this may lead to deliberately adding some difficulty to it.

It is also important to present the design brief in a way that will avoid fixation effects. If examples of existing solutions are included in the task formulation, they may have adverse consequences on the novelty of the results, especially when novice designers are involved (Agogué et al. 2014; Brun et al. 2018). Including multiple detailed requirements in the brief may also hinder innovation by providing too much focus towards specific solution paths, so a good balance should be found in formulating the brief.

### 2.5 Techniques for data collection

Various types of technique can be used for collecting data. The most frequently used ones in qualitative research, and particularly in design research, fall into the following broad categories (Yin 1994; Teegavarapu et al. 2008; Flick 2009; Blessing and Chakrabarti 2009):

(a) Observation or simultaneous verbalization. Observing designers while they design in real time, carrying out a real design task in their natural environment (industry), or a realistic or artificial design task in a laboratory. The researcher records what actually takes place during the design process. There are two main drawbacks to this technique: (1) since we are interested in conceptual design, it might be difficult to extract the design rationale and thought process from the observed protocols; (2) a conceptual design process that includes generation and evaluation of new ideas might require incubation and private time and therefore be difficult to observe during a predefined period of time.

(b) Simultaneous verbalization is a version of standard observation, in which the designers speak aloud while designing. This method aims at providing insight into the cognitive behavior of designers, which might be difficult to obtain through standard observation. The technique is considered appropriate for two or more designers who work together on a design task. According to Blessing and Chakrabarti (2009), the main drawbacks of this technique are that designers might consider it difficult and even embarrassing to think aloud while designing in the design office amongst their colleagues, and specific problems in transcribing and analyzing the recordings of teamwork: more words (data) per time unit compared to recordings of individuals, overlapping data streams because people interrupt each other and talk at the same time (a specific notation in the transcription is necessary than), parallel processes when one or more team members become engaged in another issue than the other members, and team members 'doing their own thing' in silence. Green et al. (2002) claim that when this method is applied in design research, it does not capture the practice, the strategies and the cognitive activities that designers use.

(c) Reflective questionnaire, interview or written survey. These techniques can be used for data collection as opinions and suggestions for improvements, testing the level of comprehension and identifying difficulties regarding a new design method.

(d) Analysis of documents generated during the design process. It is an efficient technique, allowing to capture the design process—cognitive activities, exploration strategy, alternative solutions that evolved during the process, decisions that were made and the rationale for choosing one solution and rejecting another, as well as the final outcome. Kroll and Shihmanter (2011) show how analysis of students' design reports written under the scheme of parameter analysis was able to capture the rationale of the design process by answering many questions such as the reasons for certain design decision, discarded ideas, and unused alternatives.

(e) Case study. This research method allows collecting and analyzing data using one or more of the previous techniques, all for a single case or multiple cases. It is defined as an empirical research method for collecting qualitative and quantitative data, with intensive investigations of an uncontrolled contemporary phenomenon, and within its real-life context. The objectivity of the cases is derived from the fact that they are studied without directly influencing them while conducting the study. Yin (1994) states that case study allows an investigation to retain the holistic and meaningful characteristics of a real-life event such as individual life cycle, organizational and managerial processes.

### 2.6 Assessment of creativity and innovation

Creativity and innovation is a common aspect in many design studies. Dorst and Cross (2001) wrote that studying creative design may be problematic because there can be no guarantee that a creative event will occur during a design

process, and because of the difficulty of identifying a solution idea as creative. However, they point out that creativity can be found in every design project, if not in the apparent form of a distinct creative event, then as the evolution of a unique solution possessing some degree of creativity. Moss (1966) identifies and estimates the creativity level of a product through a combination of usefulness and unusualness. Usefulness is determined by comparing the level of fulfillment of the product requirements with a standard solution considered correct, which is called a "teacher's solution". This parameter is measured on a scale of 0–3, where 0 corresponds to a design that does not satisfy the requirements, and 3 is assigned to a solution considered better than the teacher's. Unusualness is determined through the reverse probability of that idea appearing within a homogeneous group of solutions. It is assessed by comparing the product with similar products that solve the same problem. Therefore, this is a comparative approach for which the evaluator must be familiar with possible solutions that may appear and the frequency of their appearance. In addition, the evaluator should be able to deduce which probability of appearance is considered normal for average solutions and translate the probability deviations to an unusualness rating. This rating too has a scale of 0–3, where 0 means that the solution is very common and 3 means that it is exceptionally original. Finally, the degree of creativity is calculated by multiplying the two values, usefulness and unusualness, resulting in creativity being rated on a scale of 0–9.

Sarkar and Chakrabarti (2011) assess the creativity level of a product through a combination of novelty and usefulness. Novelty is measured by a combination of seven elementary constructs: action, state, physical phenomena, physical effects, organs, input and parts. The usefulness of a product is measured in terms of the degree of usage a product has or is likely to have in society. The scale is provided by a combination of several elements to assess usage: the importance of the product function, the number of users, and how long they use it or benefit from it. Together, these give a measure of how useful the product is to society. Shah et al. (2003) look at the design process, not just its outcome, to identify and estimate creativity. They combine measures of novelty, variety, quality and quantity. Novelty evaluates how unusual or unexpected an idea is compared to other ideas. Variety relates to the solution space explored during the design process, where the generation of similar ideas indicates low variety. Quality is a measure of the feasibility of an idea and how close it comes to meeting the design requirements. Quantity is the total number of ideas generated. The rationale for quantity is that generating more ideas increases the chance of a better solution.

Goldschmidt and Sever (2011), while studying the impact of visual stimuli on design creativity, identify and estimate the creativity level through a combination of originality and practicality. The rationale for including the practical side of the design solution with respect to creativity and innovation stems from the motivation to look for a good solution that will be useful and effective and not just any solution. There is a commonality between Goldschmidt and Sever's work and Moss' parameters in that originality is similar to unusualness and practicality to usefulness.

## 3 Developing the evaluation metrics

### 3.1 Categories and metrics definition

Evaluation metrics were planned in two categories: applicability of the process and effectiveness of both the process and its outcome. Applicability should assess the extent to which the new process model is easy to teach, learn and apply, while effectiveness relates to the degree to which the process contributes to a good solution while allowing creativity and innovation. Thus, the outcome of the process—the final design solution—should reflect on the effectiveness of the process and should be evaluated alongside the process itself.

In addition to learning from the literature survey, expert designers from industry were interviewed to help establish the metrics. The main criteria for selecting interviewees were system thinking skills and many years of experience as engineers and R&D leaders (project managers, system engineers, engineering department managers), making these professionals capable of articulating a reliable and well-founded opinion on the subject. The interviews comprised two sessions. The first consisted of an overview of the research and posing the questions to consider, e.g., what should be measured to evaluate applicability and effectiveness of a prescriptive conceptual design model? In the second session, after having thought about the subject, the interviewees communicated their opinions. The interviews began with two preliminary questions: (1) describe how you understand the objectives of engineering design and the essence and importance of the conceptual design stage? and (2) what are the expected outcomes of the conceptual design stage? The experts were then asked to list metrics for evaluating applicability and effectiveness of a design method. The interviews were transcribed word for word, including both the questions and responses. The data were analyzed by first clustering statements and words to identify central notions and reduce the amount of data, followed by identifying unique concepts.

The resulting four metrics to measure the applicability of the design method, following the literature survey, as described in Sect. 2, and interviews, were:

**Table 1** Summary of the evaluation metrics and their measurement techniques and ranking scales

| Evaluation category | Evaluation metric (what to measure) | Measurement technique and ranking scale (how to measured) |
|---|---|---|
| Applicability | Ease of teaching | Subjective evaluation by the research team after teaching the new model in class + crosschecking against the other metrics<br>Ranking scale: qualitative |
| | Ease of understanding | Analysis of reflective questionnaires and design reports<br>Ranking scale: qualitative + quantitative |
| | Ease of use | Analysis of reflective questionnaires and design reports<br>Ranking scale: qualitative + quantitative |
| | Extent of being followed correctly | Analysis of design reports<br>Ranking scale: qualitative |
| Effectiveness | Contributing to a solution that meets the design requirements (MDR) | Analysis of design reports to compute<br>$\text{MDR} = \sum_{i=1}^{n} \text{Difficulty of Requirement}(i) \times \text{Degree of Compliance}(i)$<br>Ranking scale: quantitative + qualitative (general assessment) |
| | Promoting creativity and innovation (C&I) | Analysis of design reports to compute<br>C&I = Originality × MDR<br>Ranking scale: quantitative + qualitative (general assessment) |
| | Allowing a dynamic and flexible process | Analysis of design reports<br>Ranking scale: qualitative |
| | Supporting ongoing evaluation | Analysis of design reports<br>Ranking scale: qualitative |
| | Facilitating design rationale capture | Analysis of design reports<br>Ranking scale: qualitative |

1. Ease of teaching.
2. Ease of understanding the key factors, terminology and underlying principles.
3. Ease of use.
4. Extent of being followed correctly in terms of demonstrating a clear and concise step-by-step design procedure and complying with the core principles of the method.

The effectiveness of the design method and its outcome, the designed artifact, was defined by the following five metrics:

1. Contributing to a solution that meets the design requirements.
2. Promoting creativity and innovation.
3. Allowing a dynamic and flexible process, i.e., the creation of new, previously unknown or unpredictable alternative solution paths together with moving back and forth throughout the process. The rationale behind this metric is that design requires information and knowledge, and these are acquired gradually, in an iterative process. A prescriptive design method that allows a dynamic and flexible process and assimilates new insights and knowledge created during the design—which may sometimes contradict or overrule earlier concept and decisions—seems to increase the potential of avoiding fixation on early ideas.
4. Supporting ongoing evaluation by encouraging the uncovering of weaknesses, pointing out possible areas for improvement, and screening and filtering the evolving concepts toward the most promising direction. Continuous evaluation is a mandatory feature of a good design method and should be built into it.
5. Facilitating design rationale capture. Designers tend to promote the final solution, sometimes explaining how they derived it, but without the difficulties and pitfalls encountered along the way. A detailed account of the thought process and intermediate concepts generated during conceptual design allows capturing the "justifications" and other considerations (Kroll and Shihmanter 2011). From the organizational viewpoint, documenting thoughts and intermediate concepts can be useful in the long term with respect to other design tasks. Since many designs are redesigns, a record of the design process, the decisions that were made and the rationale behind rejected concepts may be important. Concepts that do not fit a specific problem can often be the "perfect" solution to a different problem.

### 3.2 Measurement techniques and ranking scales

Having defined the evaluation criteria as the nine metrics in the two categories, the next task was to develop and characterize the techniques for measuring them together with their ranking scales, as summarized in Table 1.

Two of the metrics use formulas that need to be explained. The ranking scale that measures the extent to which the design process model contributes to a conceptual solution that meets the design requirements (MDR) is inspired by Chulvi et al. (2012), who propose a measure for determining a product's creativity and innovation and relating it to the design requirements. The outcome is that MDR is calculated by the following equation:

$$\text{MDR} = \sum_{i=1}^{n} \text{Difficulty of requirement}(i) \times \text{degree of compliance}(i)$$

where each design requirement is rated on a scale of difficulty and challenge in relation to the other requirements: A score of 3 is assigned to complex requirements, i.e., multidimensional or difficult to satisfy, while medium difficulty requirements get a 2 and the least challenging requirements, a 1. The degree of compliance with each requirement is graded on a 0–1–2–3 scale, where 3 denotes a high level of satisfying the requirement and 0 corresponds to no compliance with the requirement at all. The calculated MDR thus varies between 0 and a maximum theoretical value, and this range is later normalized to a score on a 0–100 scale.

For the ability of the design method to promote a creative and innovative solution (C&I), a variant of the approach of Goldschmidt and Sever (2011) is used:

$$\text{C\&I} = \text{Originality} \times \text{MDR}$$

where originality is ranked on a scale of 0–1–2–3 according to Moss (1966), with 0 meaning that the conceptual solution is usual, expected, based on existing solutions, or very similar to the other solutions proposed. A score of 3 means that the solution is very different and unique compared to the other solutions, it includes a combination of several unique ideas and principles, or that it presents a unique way to solve all or part of the task. The calculated C&I can reach a maximum value of three times the MDR, which we later normalize to a score of 100, and a minimum of 0, which corresponds to a 0 normalized score. This definition of C&I means that the evaluated conceptual artifact not only has to be original, but also must have the potential to be a viable and beneficial solution.

## 4 The experimental procedure

Based on the considerations described in Sect. 2, it was decided to conduct the experiment in an academic environment, during the Winter Semester (November–January) of 2016–7, in the framework of the "advanced engineering design" course in the department of mechanical engineering at ORT Braude College, Karmiel, Israel. This is a 3rd year compulsory course in which the students are taught various design methods in 2-h/week lectures, and practice them in weekly 3-h studio[2] sessions. Students in this class are required to carry out need analysis and specification development, conceptual design by the ICE method, and some embodiment design, all for an original, open-ended task assigned to the whole class. They report their work in three written reports, with the last two containing the previous, corrected report. For assessing their performance, only the conceptual design part of the second report was used. The experiment involved 55 students who worked in teams of 3–4, for a total of 16 teams. The students' background and knowledge base are typical of mechanical engineering students in the middle of their 3rd year, with little exposure to design processes and practices beyond the common machine elements class. The students themselves formed the teams, with no intervention by the course instructors.

The task selected for the experiment was to design a velocity meter for mapping ocean currents. The product should be deployed in large quantities in the oceans and the information gathered would be used to draw current maps for ships and submarines. Some customer requirements were: (1) measure flow velocities from 1 mm/s to 1 m/s in all directions; (2) the maximum depth where measurements are needed is 3000 m; (3) one measurement every hour is required, over a whole year; and (4) the sensors need to stay in the same location for 1 year. The task did not include signal transmission from the velocity meter; it was assumed that this was possible. This formulation follows the arguments made in Sect. 2.4; that is, no examples are provided to minimize fixation effects, and just a few customer requirements are specified so the solution space is large.

The evaluation was primarily based on analyzing the design reports of the participants, who were instructed to describe their work in great detail, with every design "move" included, even if unsuccessful. In addition, concurrent with turning in the conceptual design report of each team, every participant was asked to answer a reflective questionnaire. This structured questionnaire contained six open questions that were developed for this study, with particular attention given to their phrasing. The questionnaire was an additional tool that helped in evaluating how well the ICE model is conducive to teaching and easy to understand and apply. The six questions are shown in Fig. 2.

The experiment itself consisted of the following three stages:

[2] A design studio, sometimes called "clinic", is a setting whereby a small number of student teams work independently but under the supervision of an instructor. The instructor demonstrates the proper design practices and guides the students in the correct direction, but without actually solving problems for them.

**The Reflective Questionnaire**

1. Describe your general impression regarding the level of ease/difficulty in understanding the principles of the method before using it. Rate on a scale of 3 (very easy to understand), 2 (not easy but also not very difficult to understand) and 1 (very difficult to understand). Explain your answer in detail.
2. Describe your general impression regarding the level of ease/difficulty in using the method after using it in your project work. Rate on a scale of 3 (very easy to use), 2 (not easy but also not very difficult to use) and 1 (very difficult to use). Explain your answer in detail.
3. The ICE method rests upon several key principles that constitute its ideational foundation. Describe and explain in detail at least three of those principles.
4. What are the three components that appear repeatedly in the evolution of a conceptual solution? Explain and justify your answer.
5. Regarding the knowledge expansion process, explain in your own language how you see each of the three stages (initial, ongoing and final). Explain and justify your answer.
6. What do you think of ICE in general? Consider the efficiency of the process, whether it helped you carry out conceptual design, the ability of the process to encourage innovation and creativity and avoiding fixation, the suitability of the process to innovative design (designing a product that does not exist) or routine design (improving an existing product or designing a product that is similar to something that exists). Explain and justify your answer.

**Fig. 2** The reflective questionnaire used in the experimental study (translated from the original Hebrew text)

1. Instruction: A 3-h introductory lecture on conceptual design given by the first author, followed by 6 h of lecture on the theory of the ICE method with detailed demonstration given by the second author.
2. Designing: Carrying out the conceptual design stage by applying the ICE method. This took approximately 5 weeks and was done in the studio and outside of the classroom. A detailed design report was submitted by each team, and the completed reflective questionnaire was turned in by each student separately.
3. Analysis: The design reports and completed questionnaires were analyzed according to the metrics in Table 1. Some of the analysis entailed reconstructing the evolution of design solutions in the form of C–K theory's concept trees, and some aspects in judging the design solutions were carried out with the help of additional examiners, as described later.

For computing the MDR metric, five requirements were set as a benchmark, and they are listed in Table 2 along with their difficulty scores. This means that the maximum obtainable MDR score, when compliance with each requirement is 3, is 27. It follows that the maximum score possible for C&I is 81, when originality is rated at the highest value. Both MDR and C&I scores were later normalized to a 0–100 scale.

**Table 2** The five requirements evaluated for compliance by the solution and their assigned difficulty score on a 1 (easy)–2 (medium)–3 (difficult) scale

| Design requirement | Difficulty score |
|---|---|
| Measure velocities from 1 mm/s to 1 m/s | 3 |
| Measure velocities in all directions | 2 |
| Execute one measurement every hour over a whole year | 1 |
| Stay in the same horizontal location | 2 |
| Stay in the same depth | 1 |

## 5 Results and analysis of the findings

The findings will be presented and discussed in the following order: first, the overall impression from the students' work, including several general observations and the students' view regarding the new model (question no. 6 in the reflective questionnaire). Next, the findings related to the evaluation criteria categories and metrics of Table 1, starting with applicability of the design method and progressing to effectiveness of the method and the final outcome. All the findings were analyzed by the research team, and the metric for the contribution of the prescriptive model to a conceptual

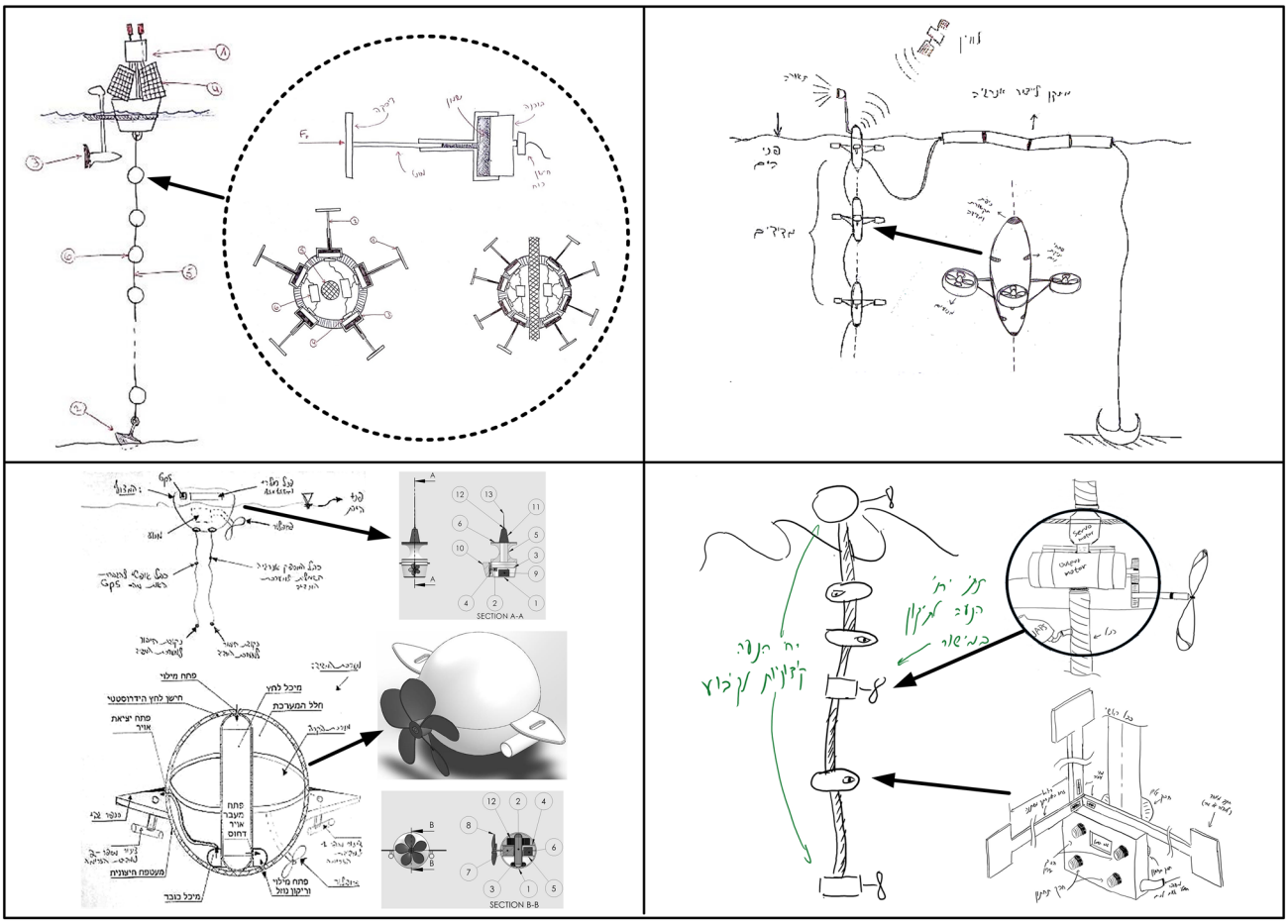


**Fig. 3** Four examples of conceptual solutions from students' reports

solution that meets the design requirements (MDR) was calculated by three additional examiners who had professional design experience. Those examiners were not the same people who helped in establishing the assessment metrics, as described in Sect. 3.1. Figure 3 presents a few examples of the final conceptual solutions generated by the participants.

## 5.1 Overall impression

The initial observations from analyzing the design reports are:

- Most of the participants realized that the task included several main functional aspects, such as the dispersion of the measurement devices and maintaining their position in the horizontal and vertical dimensions, measuring the flow velocity, and transmitting the data. They defined the basic functional attributes of the first concept $C_0$ accordingly.
- Most of the participants decided that the most difficult and challenging aspect of the task was measuring the flow velocity (E type I, see Fig. 1). Therefore, they began the design process with this aspect and only later addressed the other functions. Nevertheless, there were also teams who handled several aspects simultaneously.
- Detailed calculations and engineering assessments accompanied the design process in most of the reports in the manner in which the ICE model is intended to be implemented regarding the steps of structural synthesis and evaluation of type III.
- The design process described in the reports mostly seemed to be systematic and logical according to the various stages of the ICE model. It was possible to understand retrospectively the considerations that led to the selection or exclusion of one solution over another. It was possible to understand the critical issues identified as causing non-compliance with the requirements, and accordingly, the different decisions made about continuing the process. Overall, the design processes could be reconstructed from the reports and the various metrics established accordingly.

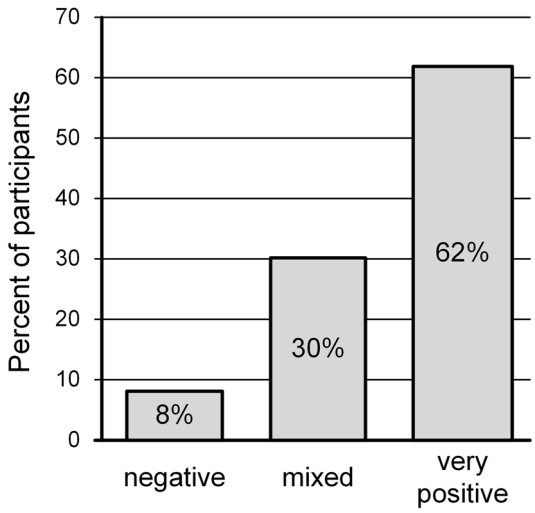


**Fig. 4** Distribution of participants' general opinion of the ICE model as expressed by their replies to question no. 6 in the reflective questionnaire

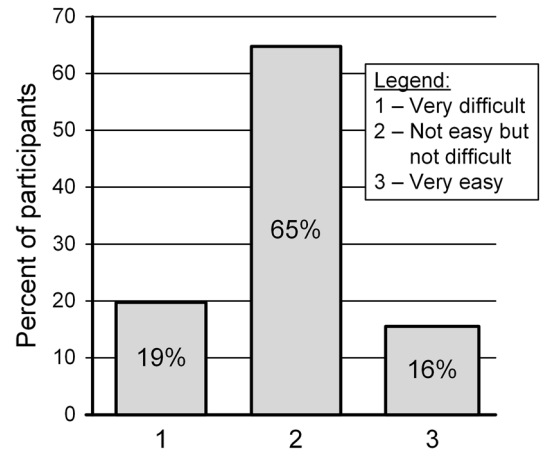


**Fig. 5** Distribution of participants' ease of understanding the model as expressed by their replies to question no. 1 in the reflective questionnaire

- Some teams tended to use existing solutions for some aspects of the task, while others offered original solutions.
- There was a large variation in the quality of the work among the teams. Nevertheless, it was decided to include all the reports in the study.
- Question no. 6 in the reflective questionnaire (Fig. 2) asked the respondents for their general opinion of the ICE model after learning and experiencing it. The students were not asked to reply quantitatively, as this was an open question. However, to analyze the answers they were divided into three categories: very positive opinion, mixed opinion and negative opinion. Figure 4 summarizes the findings. A very positive opinion of the ICE model was expressed by 62% of the participants, 30% had a mixed opinion, and 8% stated a negative opinion.

## 5.2 Model applicability analysis

### 5.2.1 Ease of teaching

The evaluation and conclusion regarding this metric are based on the students' replies to questions no. 1 and 2 in the reflective questionnaire, analysis of the design process as documented in the reports, and a subjective opinion of the research investigators, formed after the instruction stage of the experiment. The conclusion is that the new model is overall conducive to teaching. During the preparatory lessons, it was evident that the students were attentive, were able to follow what was said, and asked practical and relevant questions. All in all, the impression is that most of the students were able to understand the key factors and principles of the new model and accordingly, comprehend the new conceptual design process. However, difficulties were also identified, as will be discussed later.

### 5.2.2 Ease of understanding

The distribution of students' replies to question no. 1 in the reflective questionnaire is shown in Fig. 5. About 65% of the students thought that the model's key factors, terminology and underlying principles were not easy but also not difficult to understand, 16% thought the model was very easy to understand and 19% thought the model was very difficult to understand. This metric was also evaluated by analyzing the design reports, and it was concluded that overall, the design process was performed correctly and according to the principles of the model. This was also noted repeatedly in the comments by the three additional examiners.

One difficulty that students had, in understanding the notion of the first concept, $C_0$, had been identified in the course of analyzing the reflective questionnaires and design reports, and also from the questions raised in class during the instruction stage of the experiment. This led to several improvements and changes in the model, which are not specified here but have already been incorporated in the ICE model description in Weisbrod and Kroll (2018).

### 5.2.3 Ease of use

A summary of the students' responses to question no. 2 in the reflective questionnaire is shown in Fig. 6. About 59% of the respondents thought that it was not easy but also not difficult to apply the model to solve a design task; about 29% thought it was very easy to apply the model and 12% considered the model to be difficult to apply. This result

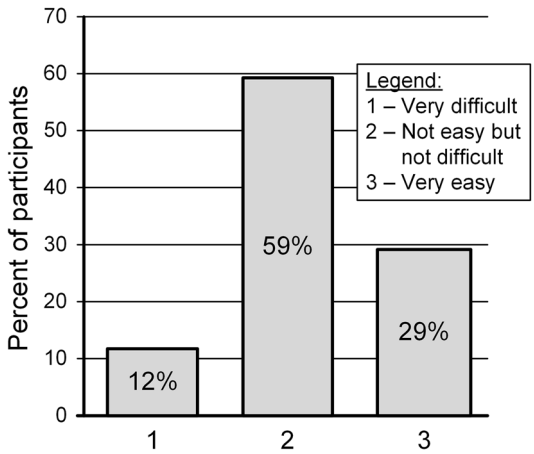


**Fig. 6** Distribution of participants' ease of using the model as expressed by their replies to question no. 2 in the reflective questionnaire

indicates that close to 90% of the participants—inexperienced students, for most of whom the conceptual design process was a relatively new subject—thought that the model could be applied to solving realistic design tasks. This finding is also in agreement with the results obtained for the next metric, which examines the design process as followed by the students.

#### 5.2.4 Extent of being followed correctly

To be judged a good design process, issues at the conceptual level (ideational attributes) should be identified, configurations should be created with quantitative hardware representations (structural attributes), and constructive evaluations should be carried out continuously. Within this metric, the quality of the executed design process was examined in terms of its underlying logic and stages. A part of the analysis of the design reports was reconstructing the design process in terms of the ideational and structural attributes that were generated. By building the concept tree and the final concept, it was possible to capture the dynamics of the design process: the concepts created in the process, the decisions that were made and the rationale behind rejected and accepted concepts. Figure 7 shows a representative example of a reconstructed concept tree. Concepts that were attempted but discarded later are crossed out, backtracking decisions are marked ("decision 3" in this case), and the "leaves" of the tree are joined to form the final conceptual solution, $C_f$.

Figure 8 summarizes qualitatively the extent of correctly carrying out the main aspects of the ICE model. Each of these aspects was rated on good–mediocre–poor/absent scale for the 16 reports.

The findings and conclusions regarding the extent of following the design model correctly, as judged from the design reports, and in particular from reconstructed concept trees as in Fig. 7, and from Fig. 8, can be summarized as follows:

- The design process began with a need analysis so that the customer's needs were analyzed and converted to a list of initial engineering requirements. In general, this stage was performed correctly.
- Next, the first concept $C_0$ was derived from the initial engineering requirements list. In most of the design reports, $C_0$ included several basic functions, such as deployment of the measurement devices to their fixed positions (some teams divided this function into two:

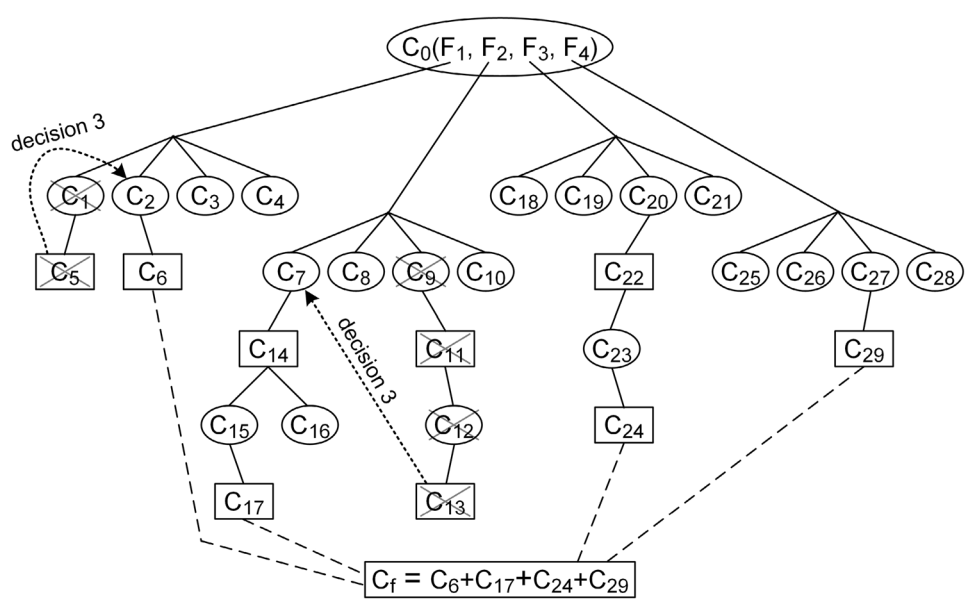


**Fig. 7** The concept tree reconstructed from one of the design reports. Concepts are numbered in the order of their development, with ellipses denoting a concept generated by ideational synthesis and rectangles denoting a concept generated by structural synthesis

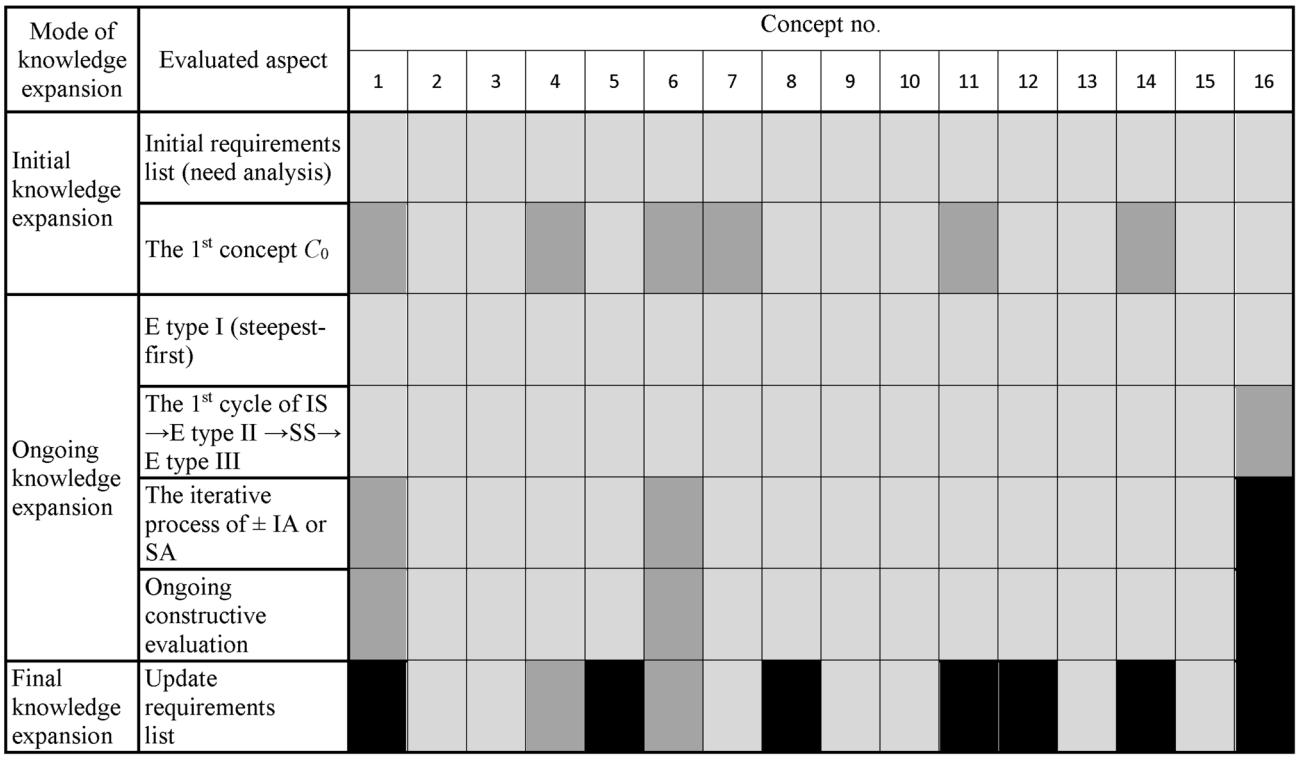


**Fig. 8** Summary of the extent of correctly following the main aspects of the ICE model. Light gray indicates good performance, dark gray indicates mediocre performance, and black means that the aspect has been carried out poorly or not done at all

deployment and positioning in the horizontal and vertical dimensions), measurement of flow velocity and direction, and data transmission. However, in some reports $C_0$ erroneously included constraints or characterizations of how well the functions should be satisfied, for example, compliance with environmental conditions, measuring at a maximum depth of 3000 m, and measuring every hour. In one report (#1), $C_0$ was defined by two basic functions: $F_1$—measuring the flow velocity in all directions, and $F_2$—deployment of the devices and staying in the same location for 1 year. They scored mediocre performance on this in Fig. 8. Another team (#3) updated their initial $C_0$ by adding two more basic functions during later stages, so their score was higher. It seems that it was not clear enough to the participants whether $C_0$ itself could be modified or updated during the conceptual design process.

- In all the design reports, an E type I evaluation operator was applied after deriving $C_0$, according to the steepest-first strategy. Most of the teams chose measuring the flow velocity and its direction as the most difficult and challenging aspect to focus on first. However, there were also reports in which several aspects were dealt with simultaneously while maintaining the interfaces among them. Some teams combined functions later in the design process. Consolidating functions may be considered desirable as it can increase reliability and reduce costs. The opposite is also possible, so basic functions that were not identified at the beginning can be added later. Combining and adding functions are consistent with the ICE model strategy, which employs the principle of solution–problem co-evolution, and it indicates that the model allows a flexible and dynamic design process.
- All the participating teams carried out the first design cycle according to the underlying principles of the ICE model. The three operators—ideational synthesis (IS), structural synthesis (SS) and evaluation (E) (of three types: I, II and III)—were used. The IS correctly implemented the strategy of divergent thinking, according to which several ideational alternative solutions are proposed and examined during the conceptual design process. However, in some reports, this was performed mostly at the beginning of the process, while later, in response to new critical issues, only a single solution was put forward. This phenomenon can be clearly seen in Fig. 7: four concepts were generated for each function in $C_0$ in the first "level" of the tree, but only one or two (e.g., $C_{23}$, $C_{15}$ and $C_{16}$) in the next level. The SS usage always complied with the strategy of convergent think-

| Concept no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Score by the research team | 70 | 93 | 89 | 85 | 81 | 67 | 30 | 81 | 85 | 78 | 85 | 85 | 74 | 85 | 78 | 60 |
| Score by the external examiners | 66 | 90 | 85 | 80 | 80 | 80 | 81 | 82 | 84 | 73 | 85 | 86 | 86 | 88 | 90 | 71 |
| Mean score | 68 | 92 | 87 | 83 | 81 | 74 | 56 | 82 | 85 | 76 | 85 | 86 | 80 | 87 | 84 | 66 |

**Fig. 9** Scores given to the extent that solutions met the design requirements (MDR) as evaluated by the researchers and external examiners, normalized to a 0–100 scale. The last line shows the mean of the two previous lines, rounded. For clarity, white background is used for MDR ≥ 80, light gray for 70 ≤ MDR < 80, and dark gray for MDR < 70

ing, with supporting calculations and detailed hardware descriptions. Finally, E type III was correctly employed in a quantitative manner, accompanied by detailed calculations.

- Most of the reports presented a good evolutionary design process, consisting of several cycles of synthesis (ideational and structural) and evaluation (types II and III), and responding to critical issues discovered during the process. However, in a small number of reports, the ongoing design process included—for each function in $C_0$—mainly one cycle of IS with multiple alternative concepts, followed by E type II to select among them, SS to implement the ideational attributes in hardware, and E type III to ostensibly converge towards a final concept. The concept trees in those reports consisted of short branches similar to the rightmost ($F_4$) branch in Fig. 7. This, of course, is not a good design process and most likely impossible, perhaps even superficial and not representing a serious effort; this dependence on the participants' attitude being a limitation of the experiment. Later we shall examine the relationship between the quality of the design process and its outcome.
- Backtracking during the design process took place according to decisions 3 and 4 in Fig. 1. In other words, if an undesired behavior of the tentative concept was attributed to critical issues that seemed unsolvable, or the value of this concept was considered to be lower than other concepts, then it was decided to stop the current path, subtract existing ideational and structural attributes, and backtrack to an existing but unexplored path or to an entirely different and new solution direction that had not been proposed earlier. This mechanism was designed to avoid fixation and was used as expected. In contrast, there were occurrences in which the designers thought that the value of the current concept was still high, that is, there was a chance that the undesired behavior could be fixed. In those cases, they appropriately attempted to improve the concept (decision 2 in Fig. 1).
- The final knowledge expansion—the refinement process in which the design task and engineering requirements are updated from an initial and ill-defined state to a final and well-defined one—was not implemented correctly in about half of the reports. This may be due to insufficient emphasis and demonstration in stage 1 of the experiment, the instruction, causing misunderstanding of this issue. Nevertheless, in the design reports that did address this aspect, it was performed well and in accordance with expectations.

In conclusion, it is clear that in most of the reports the design process was carried out well, in a systematic manner, and according to the model's principles. However, there were some findings concerning the generation of the first concept, $C_0$, that led to improvements and changes in the model, and some topics that were identified as needing strengthening during the instruction of the method.

## 5.3 Analysis of model effectiveness

### 5.3.1 Contributing to meeting the design requirements (MDR)

This is a measure of how well the new model contributes to a conceptual solution that meets the design requirements. The 16 final solutions were evaluated by 3 additional examiners, 2 of whom were blind to the research goals and experimental conditions. Each examiner evaluated about a third of the reports, selected in random. Two aspects were inspected: the extent to which the conceptual solution met the design requirements (as described in Sect. 2.2), thus making the solution viable, or whether it had the potential to be improved to become one. The MDR scores are summarized in Fig. 9.

From the results in Fig. 9, we can summarize the main findings and conclusions as follows:

- In conceptual solutions #6, #13, #15, and #16, there is a mean difference of 12 points between the score given by the researchers and that of the external examiner, with the former always being lower. The difference is

exceptionally larger for conceptual solution #7, which was judged very poor by the research team. Nevertheless, the mean MDR score is still considered usable for the purpose of this study.
- About 69% of the conceptual solutions generated by the participants received a mean MDR score above or equal to 80, about 13% received a score between 70 and 80 and about 19% received a score below 70.

To complement the analysis of this metric, the relation between the quality of the design process and that of the design outcome can be examined by looking at Figs. 8 and 9 together. The following observations and conclusions can be made:

- In all the conceptual solutions with a mean MDR score of 80 and above and solution #10 with a score of 76, the ongoing knowledge expansion stages of the design process were performed well and in accordance with the ICE model principles.
- Solutions #1 and #6, with mean MDR scores of 68 and 74, respectively, had mediocre performance in the design process. The aspects of iteratively adding and subtracting ideational or structural attributes and convergence to a final solution were too rapid. Accordingly, evaluation type II and III were carried out in a somewhat superficial or incomplete manner.
- In conceptual solution #16, with a mean MDR score of 66, the design process and final outcome were quite poor. In contrast, the design process of concept #7, which received the lowest MDR score, was carried out well: multiple ideational alternative solutions—in terms of both variety and quantity—were proposed and examined, detailed calculations and engineering assessments were performed, more than one cycle of the iterative process took place, and yet the design outcome was not good. One may suspect that the reason is a non-optimal definition of $C_0$, but there are other teams (#4, #11, #14 and #6) that also had a good design process and a weak starting point, but ended up with good design outcomes. We attribute the inferior outcome generated by team #7 to the designers' individual ability.

#### 5.3.2 Promoting creativity and innovation (C&I)

This is a measure of how well the new model contributes to successful performance in terms of creativity and innovation. This metric is first evaluated qualitatively, by looking at the final conceptual solutions generated by the participants and examining the conceptual foundation, the "ideology", behind them. Without considering the viability of the solution, some of the working principles used under several categories were:

- *Principles for measuring the flow velocity* Measuring the difference between the stagnation pressure and the static pressure using a Pitot tube; measuring the drag force exerted on an object immersed in the flow by a strain gauge and converting it to velocity; using a disk connected to a force sensor via a hydraulic amplifier; using the principle of sound propagation and measuring the velocity difference in and out of the flow direction; measuring the angle change of an object immersed perpendicular to the flow; using a mechanical device based on the principle of a rotating impeller so that the rotation speed is proportional to the flow velocity; using Faraday's law and measuring the magnetic field; using optical principles by injecting ink into a pipe and measuring the time difference for it to travel between two fixed locations; measuring the motion velocity of an object immersed in the flow using an inertial measurement unit while updating the drift by GPS; measuring bending deflection of a rod using a laser beam and converting it to velocity.
- *Principles for controlling and maintaining position* Tail vane for self-alignment with the flow; powered propeller(s); GPS; gyro compass; underwater acoustic positioning system; inertial measurement unit; a three-axis joint that allows spatial movement; water tank and pump for neutral buoyancy at the desired depth; a sonar system; serial sensing using a laser light from the lowest measurement device up to a surface buoy whose position is determined by GPS; a system of weights and cables.
- *Principles for energy supply* Batteries; backup and charging by solar panels; engine-generator set; converting the rotary motion of the measurement device created by the flow to electrical energy; wind turbine; a floating station that produces renewable electrical energy by hydrokinetic technology; a central charging station at which the measurement devices arrive periodically for charging.
- *System concept* A buoy with a central cable anchored to a weight with the velocity measurement devices distributed along the cable; autonomous measurement devices that communicate independently with a "command and control center" located above the water on a buoy; fully autonomous devices that are scattered and anchored in different locations to provide the required horizontal plane and depth-wise coverage.

The C&I metric was also evaluated quantitatively according to the expression in Sect. 3.2. First, the originality of each solution was assessed on the 0–1–2–3 scale, ignoring the issues of meeting design requirements and viability. Then, the C&I metric was computed by multiplying the

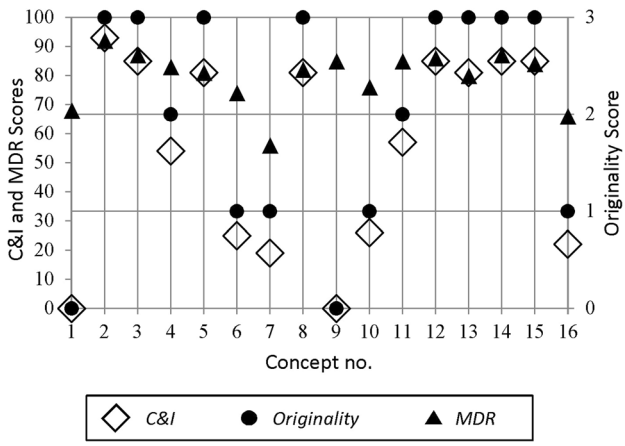


**Fig. 10** Creativity and innovation (C&I) scores normalized to a 0–100 scale alongside the originality score on a 0–1–2–3 scale and normalized MDR scores

originality score by the raw (before normalization) mean MDR score, and the result was normalized to a 0–100 scale. A summary of the results is presented in Fig. 10, including the originality score, normalized MDR, and normalized computed C&I for each of the 16 evaluated concepts.

The results of Fig. 10 lead to the following findings: 50% of the conceptual solutions who received an MDR score of 80 or greater had a ranking of 3 on the originality scale, so their C&I scores were also 80 and above. Designs with C&I scores of 67 and above may be considered highly creative and innovative. Two (12.5%) of the conceptual solutions received an MDR score of 80 or more, but had a ranking of 2 on the originality scale. Their C&I scores were 54 and 54, placing them in the middle one-third of the scores. These designs are considered to exhibit mediocre performance in terms of creativity and innovation. At the bottom of the ranking, with C&I scores lower than 33, are six (37.5%) of the conceptual solutions. Their MDR score was in most cases lower than 80 and their originality was rated 0 or 1. These solutions are considered to have low creativity and innovation.

#### 5.3.3 Allowing a dynamic and flexible process

This is a measure of how well the new model allows a dynamic and flexible process, i.e., the creation of new, previously unknown alternative solution paths together with the flexibility of going back and forth throughout the process. Reviewing the design reports and reconstructing their concept trees (e.g., Fig. 7), it became evident that backtracking took place when the designers felt that they reached a dead end with their current path. The most common was the occurrence of "decision 3", meaning that a current solution path is abandoned in favor of an existing but unexplored one. Sometimes (in about one-fifth of the backtracking cases), a "decision 4" was made, abandoning a current path and creating a completely new path. The conclusion is that the new model allows a flexible and dynamic design process according to the expectations.

#### 5.3.4 Supporting ongoing evaluation

This is a measure of how well the new model supports the continuous uncovering of weaknesses in the evolving concepts, pointing out areas for improvement, and screening towards the most promising direction. In all the design reports, it was apparent that the ongoing design process was implemented iteratively by the three operators (ideational synthesis, structural synthesis and evaluation). In most of the reports, evaluation type II and type III were applied well, to select the most promising solution path or to analyze the behavior of evolving solutions, respectively. Evaluation type III was carried out quantitatively, by presenting detailed supporting calculations, yielding constructive criticism as intended by the ICE model. Depending on the behavior of the evaluated concept, the decisions that followed the analysis by E type III moved the process towards maximizing the value of the solution. The mechanism that focuses and controls the design process so as to implement the strategy of steepest-first while thinking broadly about ideational solutions and narrowly about structural implementations, was expressed in the participants' work as expected. The conclusion is that the new model encourages a process of screening and filtering the emerging concepts, points out possible areas for improvement, and moves the design process in the most promising direction.

#### 5.3.5 Facilitating design rationale capture

This is a measure of how well the new model facilitates capturing the design rationale. The design process described in most of the reports was very systematic and logical. It was accompanied by detailed calculations and engineering evaluation steps, and it was possible to retrospectively understand the critical issues discovered during the design process that caused non-compliance with the requirements, and accordingly, the various decisions and considerations made regarding continuation of the process. Reconstructing concept trees, as in Fig. 7, was also quite straightforward, providing an overall view of how the design process had unfolded. The conclusion is that the new model allows capturing the thought processes and intermediate concepts generated during the design process, with justifications for each of the design moves. This way,

a comprehensive record of the design rationale is provided, not just a description of the final outcome.

## 6 Discussion

The testing of the new prescriptive model was not intended to establish its correctness and validity, as these are rooted in the way the ICE model had been developed by merging an accepted design theory (C–K) with a practice-proven methodology (parameter analysis). The main objectives of the experimental testing and evaluation were to determine whether the new model can be used as an effective design procedure, whether it is conducive to teaching and practicing conceptual engineering design, and whether it indeed contributes to successful design performance. Moreover, this testing was intended to be constructive: findings were to be incorporated in the ICE model to improve it.

Concurrent with the development of the ICE model itself, we investigated the use of various metrics for design methods as described in the literature, and conducted interviews with experts from industry. The outcome was the establishment of nine metrics in two categories: four for measuring the applicability of the model and five for its effectiveness. The experimental results were described in detail in the previous section, and here we discuss some of their consequences.

The combination of qualitative and quantitative analysis of model applicability shows that the new model presents a clear and concise step-by-step procedure and is conducive to teaching and practicing design. Only 8% of respondents to the questionnaire expressed an overall negative opinion about the model and only 19% thought that the model's key factors, terminology and underlying principles were difficult to understand. About 12% of the experiment participants considered the model difficult to apply in solving realistic design problems. Overall, we consider these results to be very satisfactory, considering that the model is quite complex (see Fig. 1), the students had never before been trained in conceptual design, and the design task for the experiment was relatively challenging.

In addition to obtaining results from the students' reflective questionnaires, we assessed their comprehension of the model by analyzing their design reports and reconstructing their design process in the form of concept trees (inspired by the structure of C–K theory's C-space). Here we discovered that the ongoing design process was carried out by most of the teams in accordance with the model's principles, i.e., iterative application of the three operators, IS, SS and E. We checked that the correct design strategy was implemented: divergent thinking when coming up with solution ideas and convergent thinking when implementing an idea as a configuration. Weaknesses were also noted, mainly in generating considerably fewer ideas towards the end of the design than at the beginning. The three types of evaluation were noted to have been performed well, including E type III, which requires quantitative analysis.

The effectiveness of the ICE model was assessed next, through five metrics. 82% of the conceptual solutions generated by the participating teams scored 70 and above on a 0–100 scale in meeting the design requirements, as evaluated by the research investigators and external examiners. Considering the limitations mentioned above (first time experiencing conceptual design, difficult task), we consider this result to be good and meet our expectations. To complement the analysis of the MDR metric, we examined the relation between the quality of the design process and the design outcome. We were able to identify a trend: a good process performed correctly and according to the various stages of the ICE model resulted in a favorable outcome in terms of MDR, and a bad design process resulted in a poor product. However, good and moderately good design processes were also identified, in which the design outcome was less favorable. These exceptions are attributed to the fact that the designer's individual ability is also a variable that affects the final outcome and this, of course, is difficult to distinguish. Hence, a good and systematic design process is not a guarantee of a good result, but it may certainly contribute to one.

Creativity and innovation of the solutions was evaluated to assess the contribution of the ICE model in this respect. The large variety of final solutions generated, as well as the large diversity and number of alternatives considered on the way, indicate broad, divergent thinking. This, according to Shah et al. (2003), is one of the measures of creativity and innovation. The ICE model indeed encourages a process of screening and filtering the evolving concepts towards one final solution while examining a wide range of alternatives, some of them at the ideational level only, and some with specific structural attributes, i.e., at the configuration level.

We also checked creativity and innovation quantitatively, by multiplying the score for the degree of originality with the MDR score. The results indicate that about two-thirds of the conceptual solutions were evaluated as having moderate to high C&I performance, corresponding to an MDR score of 80 or more and a ranking of 2 or 3 with respect to the degree of originality. As already mentioned, the designer's individual capabilities may come into play here, but we can still conclude that the ICE model has good potential for facilitating creativity and innovation performance.

Several difficulties and limitations were noted during the experiment and while analyzing the results:

1. Performing an experiment with undergraduate students in the framework of a compulsory course may be problematic. Some students address the design task in a

very serious and profound manner, while others show a lighter approach. Conducting an experiment with volunteers or recruiting participants through monetary compensation may alleviate this issue, but this was impractical for our experiment, which was several months long.

2. While the detailed design reports that were analyzed in this experiment proved to be a good source of information, there is always the risk that not every design move is recorded in them as requested from the participants. In particular, a person may not put an effort in describing an attempt that turned out futile later. In addition, group reports do not reflect the interaction and process dynamics among the members, so the social aspects of using the ICE method could not be studied in the current experiment.
3. In the current "information age", when the Internet provides easy access to vast amounts of data, students and perhaps practitioners too are tempted to seek the "easy way" by looking for existing solutions to their design task. Some experiments in the design area are short and done in a controlled environment, so this pitfall can be avoided. We noticed the tendency of some of the students to invest time and effort in searching the Internet instead of independent thinking, but could not completely resolve the issue.
4. Differences in personal capabilities may obscure the findings and conclusions regarding the evaluated design method. It is sometimes difficult to distinguish between an individual's weak performance and a weakness in the model itself or in explaining it to the learner. Large sample sizes of participants should help in this regard.
5. A quantitative evaluation of conceptual solutions has some degree of subjectivity, as evidenced by the difference in scores among the various examiners who looked at the MDR metric. A larger number of evaluators may mitigate this.
6. Time constraints that are characteristic of academic courses may become an obstacle. While we benefitted from the relatively long time devoted to conceptual design in our experiment—about 5 weeks—real-life design processes require incubation periods that can last many months. Studying such processes is better left to industrial settings by means of case study research.

At a more general level, we should look at the viability of testing and evaluating a design method with an educational objective. A "classical" comparative study may often be impractical, as elaborated in Sect. 2.2, so the present study demonstrates how a single method can be verified after establishing its educational goals and building the method accordingly. In our case, looking at the applicability of the method was just as important as examining its effectiveness, so a careful and thoughtful combination of evaluation metrics was needed. While the results of the study do not indicate advantages of one method over another, they can teach us about the usefulness of the tested method and to what extent it contributes to achieving its educational purpose, and pinpoint shortcomings that need improvement.

## 7 Conclusion and future work

A comprehensive process of evaluating a new design method has been described. A total of nine metrics were formulated by combining existing measures from the related literature and the opinions of expert designers who were interviewed. The metrics were used to assess various aspects of the conceptual design work of student teams to deduce the extent to which the new model is applicable and effective. The assessment involved analyzing the participants' answers to a reflective questionnaire and scrutinizing the detailed design reports submitted by each team. The reports allowed studying the design process alongside its final outcome.

The conclusion from the study is that the new prescriptive model, ICE, offers many advantages to first-time learners of conceptual engineering design. The model seems quite complex at first sight, but its deliberate formulation as a step-by-step procedure is beneficial in the learning stages. It can be assumed that after gaining more design experience, the practitioners will adopt the model's principles as a way of thinking and will not need to follow the rigid procedure so closely. A significant result of this study is the high percentage of participants who found the design model to be moderately-to-highly easy to use.

The results of the experiment described here should be considered as indicative of trends and not as unequivocal conclusions. Further experiments should be conducted in the future, including in an industrial environment, perhaps with a comparison between experienced and novice designers. The sample sizes should be large enough to overcome some of the limitations we described. Additional metrics may also be developed in the future.

Because none of the metrics used in the testing and evaluation described here are specific to the ICE method, they constitute a general set of measures that can be applied to assessing other methods individually or in a comparative study. This makes the contribution of the current work even more significant. Clearly, the set of assessment measures may also be changed, depending on the desired learning outcomes of a new educational method being evaluated. However, the lesson from the present research is that non-comparative evaluation can provide much needed information and feedback to its developers in cases where traditional comparative evaluations are impractical. Moreover, the various measures do not need to be integrated into a single metric, but can be examined and studied individually.

The method evaluated here is primarily an educational tool. It may well be that the ultimate test of an educational tool is its long-term influence on the learner. When such a method is first taught, it tends to be prescriptive, forcing the participant to follow it strictly. However, the intention of the learning process is often not to teach procedural actions, but rather, to provide the learner with the appropriate thinking skills through adopting the principles and theoretical underpinnings of the method. Thus, it would be beneficial to conduct a longitudinal study of practitioners after, say, 5 years of learning the method, and evaluate the extent to which the skills and principles have been assimilated.

**Acknowledgements** This work was supported by the Israel Science Foundation under grant number 546/12.

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**Title of the Presentation:**

Knowledge structure in design (n-dim, category theory, matroïd, spilling condition)

**Synopsis:**

This course proposes an introduction of knowledge structure in design. More specifically, this tutorial highlights why and how knowledge structure matters for generativity in design.

**Main References/ Further readings:**

Le Masson, P., Hatchuel, A., Kokshagina, O., & Weil, B. (2017). Designing techniques for systemic impact: lessons from CK theory and matroid structures. *Research in Engineering Design*, *28*(3), 275-298.

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DOI 10.1007/s00163-016-0241-4

ORIGINAL PAPER

# Designing techniques for systemic impact: lessons from C-K theory and matroid structures

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Received: 20 August 2015 / Revised: 24 September 2016 / Accepted: 28 September 2016 / Published online: 24 October 2016


**Abstract** As underlined in Arthur's book "the nature of technology", we are very knowledgeable on the design of objects, services or technical systems, but we don't know much on the dynamics of technologies. Still contemporary innovation often consists in designing techniques with systemic impact. They are *pervasive*—both invasive and perturbing—and they recompose the family of techniques. Can we model the impact and the design of such techniques? More specifically: how can one design generic technology, i.e. a single technology that provokes a complete reordering of families of techniques? Advances in design theories open new possibilities to answer these questions. In this paper, we use C-K design theory and a matroid-based model of the set of techniques to propose a new model (C-K/Ma) of the dynamics of techniques, accounting for the design of generic technologies. We show that: (1) C-K/Ma accounts for basic phenomena in the design of pervasive (and non-pervasive) techniques, in particular for generic techniques. (2) C-K/Ma, when applied iteratively, helps to propose new laws for the dynamics of techniques and helps to build strategic alternatives in the design of techniques. Moreover, C-K/Ma contributes to design theory since it provides some basic quantifiers and operations that could lead to a computational model of the process of designing techniques with systemic impact.

**Keywords** Design theory · Independence · Generic technology

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## 1 Introduction: designing for systemic impact?

In his book "the nature of technology" (Arthur 2009), W. Brian Arthur explains that looking for "some common logic that would structure technology and determine its ways and progress" he couldn't find it. Is this claim exaggerated in the light of the literature in the engineering design community? Not that much: we are very knowledgeable on the design of objects, services or technical systems. We are used to relying on elementary techniques to design them. But what do we know on the design of these "techniques"? What do we know about the dynamics of techniques?

This question is all the more relevant today because the dynamics itself might be strongly changing. Let's consider some famous technologies and their impact: software in mechanical systems (aeronautics, mechatronics), semiconductors in a large variety of systems, additive processes (or 3D printing) in industrial processes, etc. All these technologies have a "systemic" impact, they are *pervasive*—both invasive and perturbing—and they recompose large parts of the set of existing techniques. We know of some technologies that completely changed the technical environment of their time—"steam engine", "electricity", etc. One even associated each industrial revolution to a handful of such techniques. Today this process of *reorganizing* the family of techniques might be much more frequent. And it is not sure that we understand it: what is the origin of such pervasive techniques? How can we model their impact? Are there design strategies to design the techniques and their impact? And even more specifically: how can one design generic technology, i.e. a single technology that provokes a complete reordering of families of techniques?

We tend to think about these dynamics of techniques in terms of "combination" and "assembly", maybe stuck in

the "mechanical" paradigm. Or we rely on evolutionary models, with random emergence and "natural" selection. Some authors have tried to identify laws of the evolution of techniques. These proposals contributed to enlighten some facets of the dynamics of techniques but also raised difficult questions: why two independent domains of techniques become suddenly combinable? Can we differentiate between a "local" combination and a more "generic" one? Why some techniques are just locally solving a problem while other might lead to generate entire lineages of descendants?

To answer these questions, we actually lack of models. We today understand how a new "individual" emerges in the order of techniques [the logic of "individuation" analysed by (Simondon 1958)]—or we understand how the order of techniques evolves—and occasionally gets stuck [see evolutionary models or the "blocked technical systems" of (Gilles 1986)]. But we also need to overcome this separation between "individual" and "population": we need to model the design of a new "individual" with a specific effect on the "population", the design of technique with a specific effect on the set of techniques. Such a model of the design of a new technique in the set of techniques should more specifically account for critical phenomena in the design of techniques:

1. It should account for contrasted forms of design: (a) in many situations it is asked to design one product by relying on techniques, *without* designing a technique; (b) in engineering department, it often happens that designers design one new technique to develop one specific product and it asked that this new technique does not provoke a complete change in the set of techniques that this new technique is *as least pervasive as possible*; (c) by contrast, some inventors are famous for having designed techniques that provoke a complete reordering of techniques, that are strongly pervasive, that are generic and connect suddenly applications and industrial sectors that were previously unconnected. A model of the design of techniques should account for the design of non-pervasive *and* pervasive techniques.
2. It should lead to discuss basic models of the dynamic of techniques and even propose some basic laws for this. In particular, the model should help enrich basic models of "combinations" to include the logic of endogenous creation of techniques. In particular, the model should help to account for repeated design of techniques—how, over time, repeated designs interact with and transform the structure of the set of techniques.

In this paper, we tackle one specific issue for such models: our basic assumption is that modelling the design of a technique in a set of techniques should be based on modelling the interdependencies between the techniques. Understanding how one new technique is pervasive or not consists in understanding how it creates interdependencies where there were independencies and how it creates independencies where there was mutual conditioning. A new technique changes the set of techniques (or not) by changing the structure of interdependencies (or not).

Still any specific model of relations between techniques will have strong limitations. If one models techniques as graphs or as a vector in a vectorial space (as actually Suh does), one limits the validity of the model. The basic idea of this paper consists in relying on a "pure" model of interdependencies. We show that a model based on matroid theory is adapted for this (Le Masson et al. 2015a) (part 2). Moreover, recent advances in design theories open new possibilities to use a specific "knowledge model" and analyse its evolution by design (Kazakçi et al. 2010). Hence the paper proposes a model of technique design based on design theory (more precisely C-K theory) and matroid theory, a model called C-K/Ma. We show that:

1. C-K/Ma accounts for basic phenomena in the design of pervasive and non-pervasive techniques, in particular for generic techniques (part 3).
2. C-K/Ma, when applied iteratively, helps to build quantifiers, that enable to measure this impact of a new technique on a set of interdependent technique and helps to propose new laws for the dynamics of techniques and helps to build strategic alternatives in the design of techniques (part 4).

Moreover C-K/Ma contributes to design theory since it provides some basic quantifiers and operations that could lead to a computational model of the process of designing techniques with systemic impact.

## 2 Research questions: interdependences and the design of the system of techniques

### 2.1 Endogenous dynamics of technologies: the design of interdependencies

In the multiple approaches on the dynamics of technologies, we can distinguish two main trends.

1. A *first* stream of works tends to consider that the dynamics of technologies is based on the invention of new functional means. Arthur's book provides a synthesis of these approaches (Arthur 2009). Technologies are functional building blocks. The scientific study of phenomena regularly provides new building blocks. They are "*combined*" into artefacts.

Combinations are selected—for instance by the markets. Hence, the dynamics of technologies are controlled by market and science. This kind of model is used in many evolutionary economics works (Dosi et al. 1988; Saviotti and Metcalfe 1991). This approach is "exogenous": the dynamics of technologies mainly relies on exogenous forces—market and science. In this perspective, one tends to define a technique as a "functional" building block (e.g. Arthur considers that a technique is "a means to fulfil a human needs or purpose"), without considering the "combinations" issues. In this first approach, one tends to consider techniques as Lego blocks and one invention is the design of new kind of block. In the world of Lego, each new Lego block is designed to be compatible with all previously known blocks. This approach has some limits when it comes to situations where techniques are only partially compatible with each other.

As a consequence, this approach tends to neglect the issue of the design and evolution of the combinative capabilities of techniques. In particular, in this perspective, it is more difficult to analyse the emergence of techniques whose main property is precisely the capacity to assure the compatibility *between* existing techniques. Let's mention two cases: (1) when Watt and Boulton invent the cinematic for a rotary steam engine, they actually "just" make compatible the steam engine and the world of machine tools. This technique has a genericity property: it increases the genericity of the steam engine (now compatible with new applications, beyond water pumping in mines), and it increases the genericity of machine tools (now working beyond the limits of the usual energy source, hydraulic energy provided by rivers). (2) simpler illustrative case: the "swiss army knife" relies on the technique that enables to relate the different "tools" of the swiss knife—the articulation technique that enables to combine, for instance, a knife and a bottle opener.

2. Hence, a second, complementary perspective on technique: several authors, particularly in Engineering design, have underlined that for one given set of functions, there are different ways—different combinations—to address it, and these different combinations don't have the same value. In particular, Design Structure Matrices (Ulrich and Eppinger 2008), or Modularity (Baldwin and Clark 2000), or Aximatic Design (Suh 2001) lead to distinguish between technological systems, although these systems seem equivalent from a functional point of view: systems with less interdependencies (DSM), with modularity (Baldwin's Design Rules) or with independences (first axiom of Axioamtic Design) are "better"—they are said to be more robust, easier to realize, enable a large variety of alternatives, etc. In this second stream of work, one has to consider the technique in the set of all existing techniques and the structure of this set.

How should one describe this structure of the set of techniques? Several authors have noticed that the logic of "combination" is too fuzzy to describe the structures of technical systems. Precisely, Bertrand Gilles explains that, more than combinations, there are *interdependences*, "that within some limits, as a very general rule, all techniques are, to various degrees, depending on one another, so that there should be some coherence between them" (p. 19) (Gilles 1986). And consequently, Bertrand Gilles defined a "technical system" as "the coherence, at different levels, of all the technical structures, of all the technological sets and ways" (p. 19). In this approach, the technique is not limited to its functional role but is also characterized by its *interdependences* with all other techniques. As a consequence, techniques "evolve" not only because of functional challenges and/or new scientific phenomena but also because of expected interdependences between techniques. In this second approach, market and science are not the only engines in the dynamics of technological system: the techniques themselves have their own, *endogenous dynamics*.

Studying the dynamics of techniques becomes studying the *evolutions in the interdependences in the set of techniques*. On the one hand, engineering design literature has often insisted on the importance to create non-pervasive techniques. Robust design recommends to design techniques that prevent propagations in complex systems [e.g. the use of DSM tools to control and limit interactions, (Ulrich and Eppinger 2008)]. The first axiom of Suh's axiomatic design prescribes to design systems with minimal interdependencies (Suh 1990). Complementarily, on the other hand, Engineering design literature has also studied how, in certain cases, the creation of specific interdependences have a *systemic impact:* enabling "modularity" or "diagonal matrices" or providing a new "common core" (Gawer 2009; Kokshagina et al. 2013a), some techniques open access to a large variety of configurations—they enable a logic of platform, of modularity, etc. This systemic impact can be characterized by criteria like generativity and genericity: according to some authors, one should analyse the *generativity* of the design in a technical system, i.e. the new design paths that are opened by the new technique (Le Masson and Weil 2013; Hatchuel et al. 2011); other authors have underlined that one single technique can immediately enable a large set of products following a pure

"combinative" logic, i.e. with only very limited efforts, and hence the authors insist on the *genericity* of this technique (Kokshagina et al. 2013a; Bresnahan and Trajtenberg 1995). For instance, the rotary steam engine is generic because it suddenly enables new combinations of (existing) steam engines with every kinds of (existing) machines; it is also generative because it will further enable the design of completely new mobility systems like locomotives. These techniques are called pervasive because they propagate and perturb the set of existing techniques.

This quick overview of works on the dynamics of technologies helps us frame the research:

1. Phenomena: we already have a rich phenomenological knowledge base—we can distinguish between the design of pervasive and non-pervasive techniques, and we want to be able to account for the design of both types and for the repeated designs to describe the dynamics of technical systems.
2. Modelling techniques: understanding the design of technique requires to adopt *a model of technique* in which a technique is characterized by the interdependences that this technique has with the set of techniques.
3. A research issue: the dynamics of techniques is related to the evolution in the interdependences. Hence, very generally, our issue:

   - $Q_0$*: To understand the "endogenous" dynamics of technology,* we need *to model strategies for the design of techniques with systemic impact* ($Q_0$).

4. More precisely, a first research question:

   - $Q_1$: Can we find a *model that accounts rigorously for "systemic impact" on a set of interdependent techniques,* and in particular for the variety of forms, including the design of non-pervasive and pervasive techniques.

5. And a second research question:

   - $Q_2$: How does such a model predict the emergence and possibility of *strategies for the design of techniques with systemic impact* (*pervasive techniques*)? In particular, can this model at least enable to quantify such notions as "generativity", "genericity", "independence level" and how do these quantifiers help characterize different dynamics of techniques and different strategies of repeated design?

### 2.2 Design theory and knowledge structure

Design theories account largely for the impact of certain knowledge structures on the design of new artefacts. Historical analysis of Design Theories studied the effect of knowledge structure on the generative power in different cases (parametric design, systematic design) (Le Masson and Weil 2013). General Design Theory (Yoshikawa 1981; Reich 1995) shows how a knowledge structure with an Hausdorff measure warrants the design of any functional combination; Coupled Design Process (Braha and Reich 2003) shows that more generally, the set of functional combinations that can be reached depends on the "closure" of technologies, i.e. their neighbourhood of alternative technologies; in Axiomatic Design, when the DPs and FRs meet the first axiom, then larger ranges of functional requirements can be easily reached; in Infused Design (Shai and Reich 2004a, b), design capacity increases with the rules in one domain and the laws linking different domains; in C-K theory, the generative power comes from "holes" in the knowledge structure (Hatchuel et al. 2013); in Forcing, the knowledge base has to meet the "splitting condition" to enable the design of a set that is different from all already known sets (Hatchuel et al. 2013; Le Masson et al. 2016).

This review shows that *given a structure of dependences and independences in knowledge, Design Theories help to predict the impact of this structure on design capacities*. This impact can be characterized by the increase (or decrease!) in the capacity to design further original design (*generativity*) and in the capacity to obtain a large set of artefacts by combination of the newly designed technique with all previously known techniques (*genericity*). *However, they don't offer yet a computational and quantitative approach of generativity, genericity, dependence and independence.*

Now for our research topic, the question is more precisely: how do design theories model the design of a new "technology" characterized by its systemic impact? Or: how to design a specific "knowledge structure"? Actually design theories tend to favour the design of artefacts, given a certain knowledge structure; but they barely address the issue of designing a specific knowledge structure. Some insights are given in (Kokshagina et al. 2013a), based on a study of algebraic extensions with C-K theory. This study was actually made possible by one key property of contemporary design theories: they don't depend on specific objects or domains—knowledge is a "free parameter".

Hence, even if design theory did not focus until now on the design of specific knowledge structures, design theory is a favourable framework to study this question. *In this paper, we will use design theory to analyse design strategies applied on specific knowledge structures.*

Note that this will imply a theoretical restriction: C-K theory actually explains that if there is a "theory of the object" in K0, then design theory will account for the *revision* of this theory of the object. If one wants to analyse the transformation of objects *inside* one stable framework, then this framework shouldn't be changed by design, it has to be idempotent by design. This was the case with extension of algebraic structures: actually the extensions were all made into the complex field. This will also be the case in the rest of this paper: we look for a "theory of a set of techniques" that is relevant for the study of the design of a technique and its impact on a set of interdependent techniques *but* this theory has to be stable by design. Hence, in the rest of the paper we will check that our model meets this "idempotency" condition.

### 2.3 Knowledge structures characterized (only) by independences: why relying on matroids

What is the relevant knowledge structure to study design strategies with systemic impact? As seen above, we aim to *characterize this knowledge structure by dependences and interdependences*, and we expect that the knowledge structure is such that generativity and genericity can be computed.

Let's take an example: in an axiomatic design problem (a non-diagonal system, i.e. a system with linear interdependences), we can use a design theory (like C-K design theory) to design a system that meets the first Axiomatic Design axiom, hence is now diagonal (see Fig. 1 below)—in C-K, we take as knowledge base the initial non-diagonal system with its interdependences; the design process transforms the initial knowledge structure into a new knowledge structure with new independences. In this case, the knowledge base is characterized by specific interdependences in linear algebra. Let's take another example: we could take as knowledge base a functional graph (with graphical relations between functions) and design a graph with less interdependences. We use design theory to change the dependence relations in a graph or between vectors. Yet, in both cases, we are actually only interested by the *evolution of dependence relations*—be they based on linear algebra or graphs. Hence our analysis would be more general if applied to a knowledge structure that is only characterized by the interdependences between the elements—whatever the deep nature of the relation (graph or linear algebra). By chance mathematicians have already studied such a strange object in great detail: they call it *matroid*.

Matroid structures were introduced by Whitney, in the 1930s (Whitney 1935), to capture abstractly the essence of (linear) dependence. Whitney explains his project as follows: "let $C_1$, $C_2$,… $C_n$ be the columns of a matrix M". Any subset of these columns is either linearly independent or linearly dependent; the subset thus falls into two classes. These classes are not arbitrary; for instance, the two following theorems must hold: (a) any subset of an independent set is independent; (b) if $N_p$ and $N_{p+1}$ are independent sets of $p$ and $p + 1$ columns, respectively, then $N_p$ together with some column of $N_{p+1}$ forms an independent set of $p + 1$ columns […]. Let us call a system obeying (a) and (b) a '*matroid*'". (p. 509) (Whitney 1935). Hence, the description with matroids will be very general (and quite poor—as Whitney: "The fundamental question of completely characterizing systems which represent matrices is left unsolved") but it has the great advantage of only characterizing the relationship between elements in two modes: independence and dependence. And this remains valid for a large set of objects—Whitney: "In place of a matrix we may equally well consider points or vectors in a Euclidean space, or polynomials, etc." and more recently: graphs, matrices, groups, algebraic extensions, etc. (for a pedagogical introduction to matroid, see (Neel and

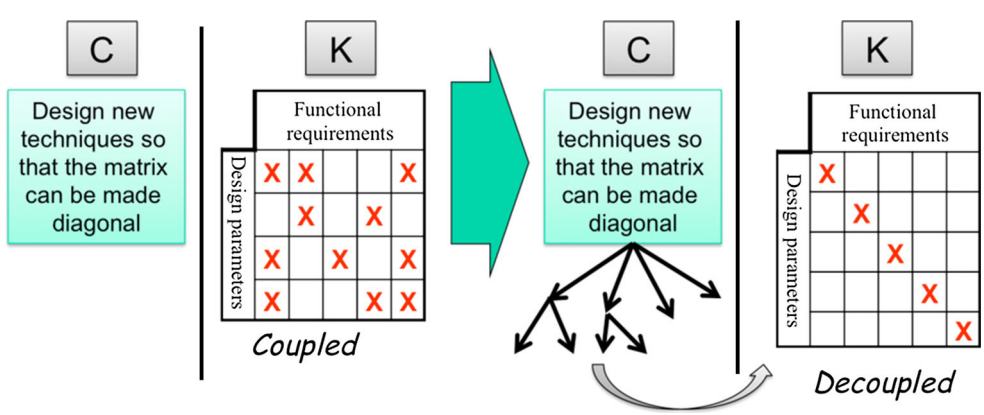



**Fig. 1** Designing a diagonalized matrix—*left-hand side* before design; *right-hand side* after design, the knowledge structure has changed

Neudauer 2009); the reader can also refer to the table presenting the definition of the main matroid notions used in this paper, in "Appendix"). In particular, it means that our two examples above (with vectors in Suh axiomatic or with functional graphs) could be addressed with the same formalism.

In matroid, *independence is not based on a specific type of relation.* We don't need to specify the relation: it is enough to know that there is such a relation as soon as, for a finite set $E$, there is a collection $I$ of subsets of $E$ such that $I$ satisfies the following properties: (1) $I$ is non-empty; (2) every subset of every member of $I$ is also in $I$ ($I$ is *hereditary*); (3) if $X$ and $Y$ are in $I$ and $|X| = |Y| + 1$ (the operator $|\ldots|$ designates the number of elements in a set of elements), then there is an element $x$ in $X$–$Y$ such that $Y \cup \{x\}$ is in $I$ (*independence augmentation* condition). The elements of $I$ are called the independent sets of $M(E)$, a matroid on $E$.

Note that the third axiom is critical: if one keeps only the two first axioms, one has a very general theory of independence—but it can't account for usual mathematical independences in graphs or vector spaces. The third axiom (axiom of independence augmentation) puts a strong constraint on the independence structures but helps account for classical specific models of independences.

Some comments:

- Independence or dependence in matroid theory is *not* a property of an element but it is a property of a subset of elements.
- This axiomatic seems restrictive in the sense that not all sets of elements follow these axioms. Actually this is the condition to speak of independence with rigor—more precisely with the same rigor as one speaks of independence in vector space or independence in graph (or in several other mathematical formalisms). And more generally, the matroid axioms are actually valid for a large range of relations.
- In this paper, we will often illustrate the results with *graphic matroids,* i.e. a matroid that can be represented by a graph. Not all matroids are graphic. Still the results are actually valid more generally for every form of matroid. For example, we will apply our results to uniform matroid that are not graphic in general.

Hence this paper aims at understanding the "*endogenous*" dynamics of technologies by applying design theory on a knowledge structure modelled with *matroid*. We first model elementary operations (part 3) and show that these elementary operations correspond to basic phenomena in the design of techniques (and still follow the "idempotency" condition mentioned in 2.2: the design doesn't modify the matroid model)—then we propose quantifiers to model the impact of the design of techniques on a set of interdependent techniques—this leads to analyse the variety of strategies for the design of techniques that impact a set of interdependent techniques and this leads to propose new laws for the dynamics of a set of interdependent techniques.

## 3 A C-K model with matroids

### 3.1 Notions of techniques, systems and independences in a matroid framework

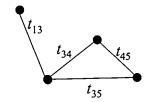
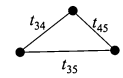
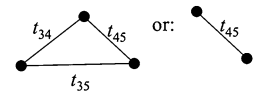
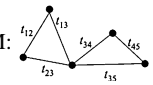
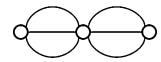
To build a C-K model with matroid, we introduce the matroid of known techniques as the K-space in C-K. Assume E, a list of known elementary techniques: $T_1,\ldots T_n$. We select a subset of this set of elementary techniques. If they build a working system,[1] we will say the subset is *dependent*; if not, it is *independent*. A working system can be minimal when all subsets are independent—it is impossible to remove one element without transforming the dependent set into an independent one. Such minimal dependent set is called a circuit in matroid theory (and it is called a cycle in graphic matroid). Hence a working system contains at least a circuit. And we call a minimal working system a working system that is a circuit.

Note that the notion of "*dependent*" relates also to a very basic notion for a minimal working system: we say that a (minimal) working system is a "dependent" set of techniques because (for the techniques that belong to one minimal circuit contained into the working system) if one technique is out of order, i.e. it is removed from the working system, then the system doesn't work anymore, it is no more a working system, and it becomes an independent set. One can say that *the existence of the minimal working system "depends" on the set of the techniques that compose it*.

In general, a set of elementary techniques is *not* necessarily creating a working technical system—in matroid terms: the elements are not necessarily dependent. Still we could consider one particular case, a "lego-like" matroid of technological system, in which every set of two (or more) elementary techniques is said dependent (i.e. it creates a working "lego")—this corresponds to a specific matroid, called the uniform matroid $U(1, n)$ (where n is the number

[1] We have here a terminology issue. We will distinguish two "systems", inherited by two disciplines. On the one hand, Bertrand Gilles, as an historian, speaks of "technical system" to designate the set of all techniques and their relationships. This is what we model with a matroid, the matroid of all known techniques. On the other hand, the authors of engineering systems speak of a "system" to designate a working assembly of techniques—this is a subset of the set of techniques, this set having the "working" property. This is what we call a "working system" in the matroid model. This is actually a dependent set of the matroid. The "smallest" dependent set are circuits (also called cycle in a graphic matroid) (see Table 1).

**Table 1** Notions in the dynamics of techniques and notions in matroid theory

| Dynamics of techniques | Matroid theory | Illustration with graphic matroid |
|---|---|---|
| Elementary technique | An element in a matroid |   |
| Working system: a system made of compatible techniques (techniques that work together) | A dependent set, contains at least a circuit (a cycle) | Extracted from M below   |
| A minimal working system: each technique is indispensible for the working system to work | A circuit (a cycle in graph matroid) | Extracted from M below   |
| A family of techniques: a subset of techniques such that no "external" technique is compatible with the techniques in the family | A flat, extracted from a matroid | Extracted from M below   |
| The structure of techniques | The matroid (of techniques) | Matroid M:   |
| The structure of minimal working systems | The dual of the matroid of techniques |  |

of elements in E). Hence, a first result*: a simple "lego-like" combinatorial model corresponds to the uniform matroid*.

To give a "visual" example: suppose that the matroid of techniques is graphic. It means that it can be represented by a graph G where each elementary technique is an edge $t_i$ [E = E(G), i.e. the set of edges of the graph] and the circuits of the matroid are the cycles of the graph. Following the definition above, a *working system contains a circuit in the graph* (a path of elementary techniques that is connected and all vertices are of degree 2, i.e. the circuit goes only once through each vertex). This means a set of elementary techniques will be considered as a "working technical system" if and only if it contains a *circuit* that links some of them. It is a minimal working system if it is a circuit.

It is important to underline that this model fits perfectly with our requirements on a model of techniques (see Sect. 2.1): in a graphic matroid model, an elementary technique, i.e. an edge, is characterized by its relations with the other techniques—i.e. whether it builds dependent or independent sets with other edges, i.e. whether it can be included in a working system with other techniques.

For instance, the graph G below can be interpreted as a synthesis of the technological know-how of a designer. The designer knows the working system $\{t_{12}, t_{13}, t_{23}\}$; he doesn't know any minimal working system involving $\{t_{34}, t_{45}\}$. A matroid can be associated to this graph of a designer's knowledge, the matroid defined by the cycles of the graphs. In this, matroid $\{t_{12}; t_{13}\}$ is independent, whereas $\{t_{12}, t_{13}, t_{23}\}$ or $\{t_{12}, t_{13}, t_{23}, t_{45}\}$ is dependent. Note that $\{t_{12}, t_{45}\}$ is also independent.

We model the dynamics of technologies in matroid basic notions: a technique, a working system, a family of techniques, the structure of all techniques, and the structure of all working systems (see below).

Note that matroid theory provides immediately one quantifier: a matroid has a certain rank, which actually corresponds to the size of the largest independent set. In a graph $G$, we have the rank function $r(M(G)) = |V(G)| - 1$. Here $V(G)$ is the number of vertices of the graph $G$. $r(G) = 4$ in the example above. The rank corresponds to the highest number of techniques in an independent set: at most the graph $G$ above enables to gather (in a independent set) four edges, hence four "independent elementary techniques".

We have now a model of a set of techniques as a matroid. This raises some comments regarding the modelling logic: to what extent does it capture the reality of techniques?

1. Like always with a model, it doesn't account for every aspects of techniques—it more precisely aims at accounting for one critical aspect we want to address in this paper: interdependencies.
2. One can at least note that it is compatible with other models of techniques we find in the literature: for instance in Suh axiomatic design techniques are design parameters that address multiple functions—hence they are vectors and they can be independent as vectors are independent in a vector space. One can describe this logic of interdependencies of Suh axiomatic with a matroid model. As will be explained in more detail later, a set of $n$ DPs that follow the first

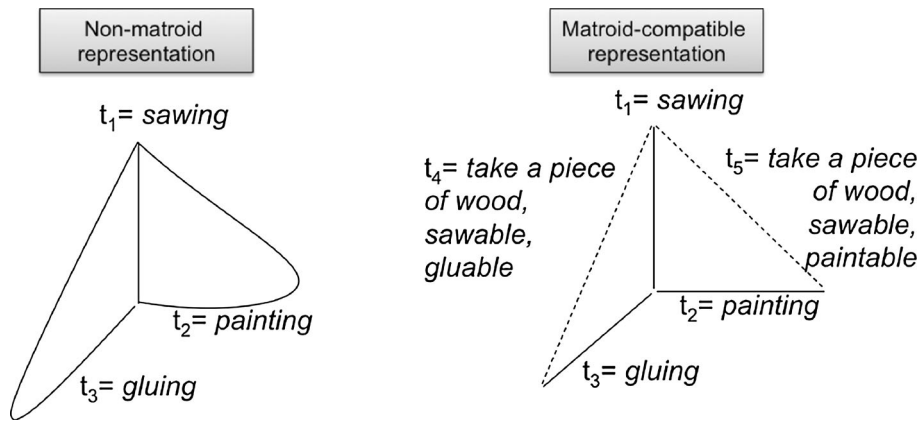



**Fig. 2** Matroid perspective to support the analysis of technical object. *Left* one takes into account three techniques $t_1$, $t_2$, $t_3$. $t_1$ and $t_2$ are used both in a working system, $t_1$ and $t_3$ are used in a working system, but $t_1$ and $t_3$ are independent: this doesn't fit with a matroid model—and actually cannot be drawn with a graph. *Right* the matroid model leads to identify $t_4$ and $t_5$ such that the working systems are preserved and the dependent relationship between techniques is preserved: $t_1$ and $t_2$ are in a working system, $t_1$ and $t_3$ are in a working system, $t_2$ and $t_3$ are independent

axiom to meet $n$ FRs can be represented by the $U(n, n+1)$ matroid (see below, paragraph 4.1.1 and 4.3.2).

3. Every set of techniques with relationship between techniques is *not* necessarily following a matroid model. We thank one reviewer for the following simple counter example: suppose a set of techniques $\{t_1 = \text{sawing}, t_2 = \text{painting}, t_3 = \text{gluing}\}$ where $\{t_1, t_2\}$ and $\{t_1, t_3\}$ are said "dependent" (by sawing and painting and by sawing and gluing one obtains two types of wooden toys) and $\{t_1\}$, $\{t_2\}$, $\{t_3\}$ and $\{t_1, t_2\}$ are said "independent". Then, this set doesn't follow the matroid axioms (by the independence augmentation condition, $\{t_1\}$ and $\{t_2, t_3\}$ are independent hence $\{t_1, t_3\}$ should be independent). Still the matroid model rather helps to reason with rigor on the notion of independence: on the example above, the matroid model leads to say that the notion of "independence" used in this example is not well-formed in the sense of matroid, and hence, there is a risk to lead to internal contradictions when one then uses the matroid model.
4. Reciprocally, one can also try to model a set of techniques in such a way that it fits with a matroid model in order to be able to analyse the properties of the model (Fig. 2). In particular, in the above mentioned example, we can set the modelling issue this way: we want to propose a matroid that meets the following requirements: the set of techniques contains at least $\{t_1 = \text{sawing}, t_2 = \text{painting}, t_3 = \text{gluing}\}$ and where $\{t_1, t_2\}$ and $\{t_1, t_3\}$ are, respectively, *included in working systems* (by sawing and painting and by sawing and gluing one obtains two types of wooden toys) and $\{t_1\}$, $\{t_2\}$, $\{t_3\}$ and $\{t_2, t_3\}$ are *independent*, this time in the sense of matroid. Is there a matroid that meets these requirements? Let's introduce $t_4 =$ "take a piece of wood that is compatible with sawing and painting" and $t_5 =$ "take a piece of wood that is compatible with sawing and gluing", and such that $\{t_1, t_2\}$ is actually included in $\{t_1, t_2, t_4\}$ that corresponds to the working system "wooden toy by sawing and painting", hence is dependent and $\{t_1, t_3\}$ is included in $\{t_1, t_3, t_5\}$ that corresponds to "wooden toy by sawing and gluing" and is also dependent (we have the same wooden toys). $\{t_2, t_3\}$ is still independent (see illustration below). This structure follows the matroid axioms. And it becomes possible to make rigorous deduction on the interdependence relations in this structure, without a risk of formal contradiction. In particular, here we say that $\{t_1, t_3, t_4, t_5\}$ is dependent which means that "$t_4 =$ take a piece of wood that is compatible with sawing and gluing and $t_5 =$ take a piece of wood that is compatible with sawing and painting, and $t_2 =$ paint and $t_3 =$ glue" can also lead to another wooden toy.
   Hence, the "ordinary" language applied to techniques can be misleading when it comes to "independence"—and a matroid model of independence can also help build models of techniques in which the notion of independence is controlled and corresponds to matroid theory.
5. More generally: can every set of techniques be modelled to follow the matroid axioms? We won't address this question here—this is not self-evident. In the rest of the paper, we will make the assumption that the matroid axioms apply. The results are obtained by admitting this assumption.

### 3.2 Designing a new matroid: a C-K design process on matroids

How does C-K apply to a knowledge base made of a matroid? We have to see how each classical notion of C-K is applied in case of a matroidal knowledge base.

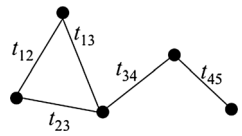



**Fig. 3** Graph G

In C-K theory, K is the space of propositions that have a *logical* status. *The logic in matroids is based on dependency*: the proposition "there is a minimal working system including technique $t_i$" is true if and only if there is a circuit $C$ containing $t_i$. On Fig. 3, $\{t_{12}, t_{23}, t_{13}\}$ is independent, hence the proposition "there is a circuit that contains $t_{12}$ in the matroid M(G)" is true; the proposition "there is a circuit that contains $t_{34}$ in the matroid M(G)" is false.

In C-K theory, C is the space of propositions that are *interpretable* in K and *undecidable* in K. Interpretable: if K is modelled as a matroid, the proposition in C must also be expressed in matroid language, and hence, it is a proposition on some of the elementary techniques of the matroid. For instance: "there is an elementary technique (i.e. an edge) such that there is a circuit that contains $t_{34}$". The latter proposition is interpretable. It is also undecidable—it is neither true nor false in the matroid interpreted as a model of elementary techniques. One design for this new edge might be an edge $t_{35}$, or $t_{25}$. Hence, we can formulate a concept for a matroidal K-base in C-K.

What is now the design process? Matroid theory teaches us that there are only *three basic operations*—design by deletion-contraction, design by extension and design by coextension (Oxley 2011). We will show (Le Masson et al. 2015b) that these operations in matroid correspond to the three very specific, contrasted ways to design techniques that we described in the first part and are well known in the literature: designing one working system without designing a new technique, designing one new working system by designing one non-pervasive technique, or designing a pervasive technique (see synthesis table below).

This is one surprising result of C-K/Ma: it helps to clarify well-known archetypes in the design of techniques (Table 2).

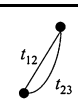
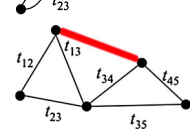
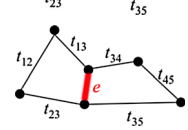
### 3.2.1 *Trivial cases: deletion and contraction*

To begin, let's first analyse the classical design issue that consists in designing one "working system" by using existing elementary techniques, while respecting their interdependences. We call it "trivial" case, because no new edge (no new elementary technique) is designed. It actually consists in "picking up" existing techniques to realize one new working system. In matroid terms, it consists in "extracting" one specific dependent set from the initial matroid by relying on two operations that keep the matroid structure, namely deletion and contraction.

How can one describe the design process? Deletion and contraction in matroid generalize deletion and contraction in a graph:

- Deletion in a graph consists in skipping an edge. *Deletion is equivalent to decide to* not *use a elementary technique for a certain design.* In the example below: to design the working system $\{t_{12}; t_{23}; t_{13}\}$, one deletes $t_{34}$ and $t_{45}$. More generally, in a matroid, deletion can be defined as follows: given a matroid $M = (E, I)$ and an element $e$ of $M$, deletion is the operation that forms the matroid $M\backslash e$ by removing $e$ from $E$ and keeping the independent sets of $I$ that are included in $E$-$e$.
- Contraction in a graph $G$ occurs relative to a particular edge, $e$. The edge $e$ is removed and its two incident vertices, $u$ and $v$, are merged into a new vertex $w$, where the edges incident to $w$ each correspond to edges incident to either $u$ or $v$. One writes $G'$ the new graph and one writes $G' = G/e$. Contraction is equivalent, in linear algebra, to a projection in a space orthogonal to the contracted element. Contracting an edge in a cycle

**Table 2** Design operations in the dynamics of technique and in matroid

| Dynamics of techniques | Matroid theory | Illustration with graphic matroid |
|---|---|---|
| Designing one working system based on existing techniques | Extracting one circuit |  |
| Cumulative design of working systems with new technique linking other techniques and minimizing propagations (non-pervasive) | Extension<br>i.e. one dependent edge, depending on the techniques to be linked together |  |
| Designing a pervasive technique, generic to several technical families | Coextension,<br>i.e. one independent edge common to several connected components |  |

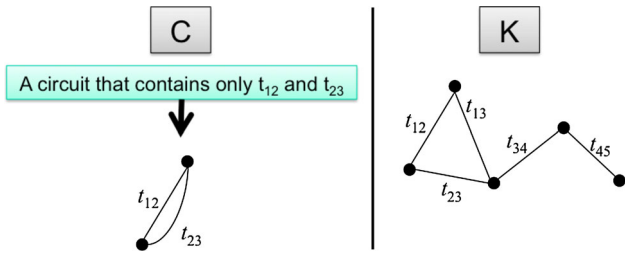



**Fig. 4** Design by deletion and contraction

actually means that *a working system can be "reduced" to smaller one with less elementary techniques* (see Fig. 4) (e.g. a refrigerator without cooling system becomes an isothermal box). For instance the concept "a circuit that contains only $\{t_{12}; t_{23}\}$" is obtained by contracting $t_{13}$ (and deleting $t_{34}$ and $t_{45}$). More generally, in a matroid $M$, contraction actually corresponds to deletion in the dual of the matroid $M$. The notion of dual will be introduced later.

More interesting are cases where the concept actually leads to design a new "bigger" knowledge structure—i.e. the concept addresses the *whole* matroid, and not only a subpart of it and the process will "grow" the initial matroid M, in such a way that the new matroid N will "contain" the old one. For these non-trivial cases, matroid theory tells us *two ways to design new edges in a matroid: extension and coextension*. We analyse these two ways and their respective consequences on the structure of the matroid of techniques.

### 3.2.2 *Extension: or the design of a non-pervasive technique*

Extension is the reverse operation of a deletion: if a matroid $M$ is obtained from a matroid $N$ by deleting a non-empty subset of $E(N)$, then $N$ is called an extension of $M$. In particular, if the subset is a simple edge $\{e\}$, then $N$ is a called *single extension* of $M$ (see the example in the figure below, we add $t_{35}$ as a new edge in $M(G)$).

**What is the systemic impact of extension?** To analyse the systemic impact, we need one additional notion from matroid theory, namely the notion of *flat*: a flat $F$ is a set of elements of $E$ such that it is impossible to add a new element of $E$ into $F$ without changing its rank. In the matroid $M$ in Fig. 5, $\{t_{12}, t_{23}, t_{13}\}$ is a flat and $\{t_{12}, t_{13}\}$ is not a flat; $\{t_{34}, t_{45}\}$ is also a flat. One says that a flat is a "*closed*" set in a matroid. A flat can be seen as a "family" of elementary techniques that are incompatible with any other elementary technique outside the family—for instance, we can consider that the family of techniques used in automotive industry is a flat because these techniques are said incompatible with any other techniques from another industry. The set of flats forms a lattice (with the inclusion relation). This lattice of flat represents the families of technologies and their inclusion relations. For instance, one represents below (Fig. 6) a matroid and its lattice of flats.

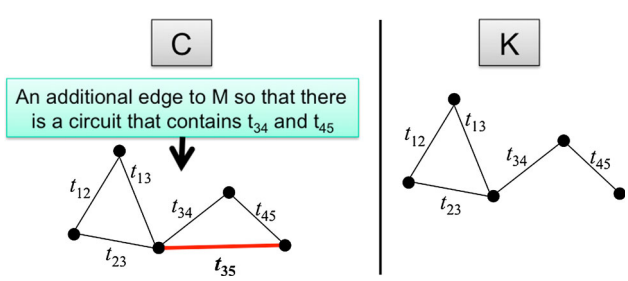



**Fig. 5** Design by extension

The systemic impact can be modelled as the impact of the design of a new edge $e$ on the structure of flats. When $M$ is extended with a new edge $e$ to form the matroid $N$, we know from matroid theory that there are three possibilities for any flat $F$:

- *Type* 1 *"e-independent flats"*: $F \cup e$ is a flat of $N$ and $r(F \cup e) = r(F) + 1$—it means that *the new edge is independent of the flat*. If $t_{35}$ is added in $G$ above, then $\{t_{12}, t_{23}, t_{13}\}$ is such a flat in $G$. These are all the flats that are *not "impacted"* by the design of $e$. More generally, these are the flats below the red line on Fig. 6c.
- *Type* 2 *"e-determining flats"*: $F \cup e$ is a flat and $r(F \cup e) = r(F)$—it means that *the new edge e is actually dependent on the edges of F*. If $t_{35}$ is added in $G$ above, then $\{t_{34}, t_{45}\}$ is such a flat in $G$. These are the flats above the red line on Fig. 6c. Note that these flats follow a certain structure: they form the so-called modular cut, which means that they are ordered by inclusion and *there is a smaller flat, which is included in all other type 2-flats* (in our case: $\{t_{34}, t_{35}\}$ is included in $\{t_{12}, t_{23}, t_{34}, t_{45}\}$). This smaller flat actually *determines* the new edge [the demonstration would require more space, see theorem 7.2.3 in (Oxley 2011)].
- *Type* 3 *"e-determined flats"*: $F \cup e$ is not a flat of $N$—it means that some other elements should be added to $F \cup e$ to "close" it into a flat, i.e. there are "old" edges of $M$ that are now dependent on elements of $F \cup e$. *e has created new dependencies*. One example is $\{t_{34}\}$ in $G$: $\{t_{34}, t_{35}\}$ is not a flat, since $t_{45}$ can be added without changing the rank. These are the flats on the red line in Fig. 6c.

Hence, the impact of extension on the lattice of flat: (1) the extension "keeps" several flats unchanged (type 1 flats). (2) The effect is confined to one "smaller" flat (here $\{t_{34}, t_{35}\}$) and all the flats that contain it, and in these flats, the extension does not change the rank—hence it creates

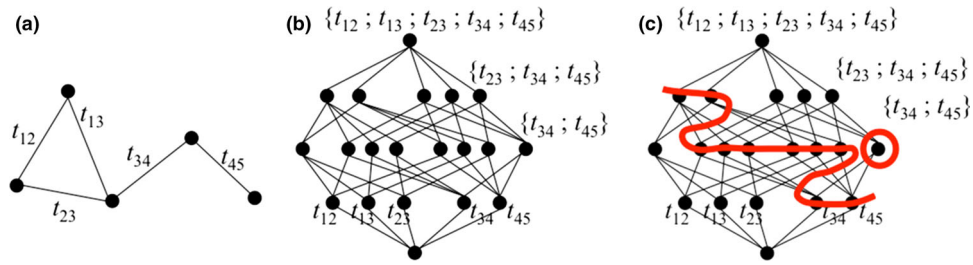



**Fig. 6** **a** A matroid, **b** its lattice of flats and **c** the effect of the extension $t_{35}$ on these flats

new dependences (same rank with more edges), i.e. it creates new cycles, i.e. it creates new "working systems". *Extension corresponds to the design of a technique that creates new systems inside one family* (*and inside all the families that contain it*) *and is non-pervasive for all the others. This is a non-pervasive technique that creates new working systems.*

**What is the design strategy? The concept: designing a new working system.** With the elements given above, it appears that extension actually corresponds to *one* new dependence inside one target family of techniques (the smaller type-2 flat). Hence an extension corresponds to a *concept:* "given (at least) two independent techniques in the matroid of techniques $M$, designing an edge $e$ that is added to $M$ to create in $M$ a new working system that contain these techniques".

This result helps to understand very important distinctions in the notion of "combination" when dealing with the dynamics of techniques:

1. *we can distinguish between a "new" working system* (*a "new combination"*) *and a working system that was deducible from the existing techniques* (*a "known combination"*): extension corresponds to the design of one *new* working system; the new working system was *not* in the matroid of techniques, *it was not "decidable" in the initial matroid*. Otherwise, the working system was not a concept, and it was already true in the matroid.
2. *we can distinguish between the design of a new working system* (*by a combination of deletion-contraction*) *without taking into account the interdependencies with other techniques, and the design of a new working system taking into account all the interdependencies with previously known techniques*. The former case would correspond to the design of $\{t_{34}, t_{35}, t_{45}\}$, "extracted" from $M$ ("forgetting" all the properties of dependence or independence with all the techniques); by contrast, an extension is driven by the design of one new working system but it also "controls" the impact on the whole matroid of techniques. The final result of the design is *not* limited to $\{t_{34}, t_{35}, t_{45}\}$ but is the matroid $M \cup t_{35}$ (that contains in particular the working system $\{t_{34}, t_{35}, t_{45}\}$ but also all the dependences and independences).

To conclude on extension, its design and its systemic impact: *extension models the design of a "non-pervasive" technique*; extension models the cumulative, non-pervasive creation of new working systems.

*We could say that a good engineering department should design by extension: based on* (*the matroid of*) *known techniques, it designs one new technique to get a new working system, it cumulates the knowledge techniques and designs the new technique for the new working system by minimizing the impact on the other techniques.* By contrast, deletion-contraction corresponds to one single project that takes advantage of existing techniques but doesn't assure backward compatibility of the new working system with initially known techniques.

Note that we better understand how an engineering department deals with combination:

(a) It invents a new combination that did not exist before (there is a new edge)—this is different from the identification of a combination that was already known.
(b) This combination takes into account the interdependencies with all other techniques—this is different from an opportunistic extraction of techniques without taking care of compatibilities.

### 3.2.3 *Coextension: or the design of a technique with systemic impact*

Coextension is the reverse operation of a contraction. In matroids, $N$ is a coextension of $M$ if there is some set $T$ such that $M = N/T$. Since a contraction operation in matroid is analogous to a *projection* (along T) [see (Oxley 2011), chapter 3.3]. *Coextension is analogous to the reverse of a projection* [see (Oxley 2011), chapter 7.3], i.e. an *expansion*.

This operation can also be seen as an *extension of the dual* of the matroid: if $N^*$ is an extension of $M^*$, then $N$ is a

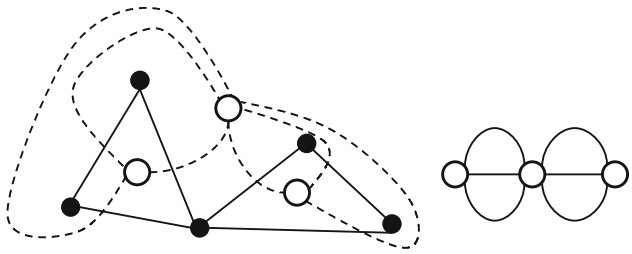


**Fig. 7** Graph and its dual. On the *left*, *black dots* the initial graph G; in *white dots* and *dotted lines* on the *left* the dual G* of G. On the *right*, the same dual G* without the underlying G

coextension of *M*. And we know quite well now what extension means in a matroid. Hence understanding coextension requires to understand what is the dual of a matroid. What is the dual *M** of a matroid *M*? Formally speaking, *M** is defined over the same set of edges as *M*; it can then be defined by its bases (a maximal set of independent edges—i.e. from this set one can regenerate all the other techniques that are dependent on this maximal independent set): given a basis *B* of the set of basis of M, a basis of *M** is the set obtained by *E*(*M*)-*B* (this definition is acceptable because it can be proven that the set of all the "complementaries" of basis of M forms a set of basis of a matroid, that is called *M**). The dual of a matroid M can also be defined by *the connected components* of *M*. We speak here of 2-connectedness (usual connectivity in a graph is 1-connectedness): a connected component of a matroid *M* is a matroid *N* of *M* such that for every pair of distinct elements of *N*, there is a circuit containing both. In the particular case where the graph G is planar (no edges are "superimposed" in the plan), it is possible to represent the dual as in the Fig. 7. If one studies a matroid of techniques, then *connected components correspond to working systems* (*elementary one: these cannot be obtained taking two smaller working system*), *hence the dual is the set of relations between* (*elementary*) *working systems*.

Hence coextension consists in putting two previously independent (elementary) connected components into a bigger one, without creating a new (elementary) working system. In terms of working systems: $\{t_{12}, t_{23}, t_{13}, t_{34}, t_{45}, t_{53}\}$ was a non-minimal working system; it becomes a minimal one. Designing an additional edge in a matroid by coextension can be represented by the figure below: in K, the matroid and its dual; in C, one possibility to extend the dual and to deduce the coextended matroid *N* (Fig. 8).

We can illustrate the coextension logic, and its difference with extension, on the practical example below. Suppose one knows techniques to make knives and techniques to make bottle openers. By extension, one can take one technique of the "family" of knives and another from the family of bottle opener and make them dependent by designing one additional technique—namely the insertion of a bottle opener in the knife handle: this is an extension. A coextension is a technique to use all the previous knifes and bottle opener techniques: the articulation of the tools on one handle is the technique that enables to design swiss army knives (Fig. 9).

**What is the systemic impact of coextension?** Let's analyse the impact of coextension on the matroid, contrasting it with extension (we won't demonstrate the properties below, they are relatively classics in matroid theory [see (Oxley 2011)—we rather insist on their consequences in the perspective of the dynamics of technologies]:

(a) Extension *preserves* the rank and creates a *new dependent* edge in a flat—hence extension creates a new working system using the new technique. We can consider that the new working system is a "*direct value*" of the extension. By contrast, coextension creates a *new independent* edge and *increases the rank*. This means that the new elementary technique (the new edge) is *not* included in a "new" working system combining elementary techniques that couldn't be combined before. If one considers that the direct value of design is in the new working systems that use the new technology—then *coextension doesn't create direct value*! The value created by the new edge is not self-evident.

(b) Extension is non-pervasive: it modifies only the flats that include the newly created working system. By contrast, coextension doesn't create a new working

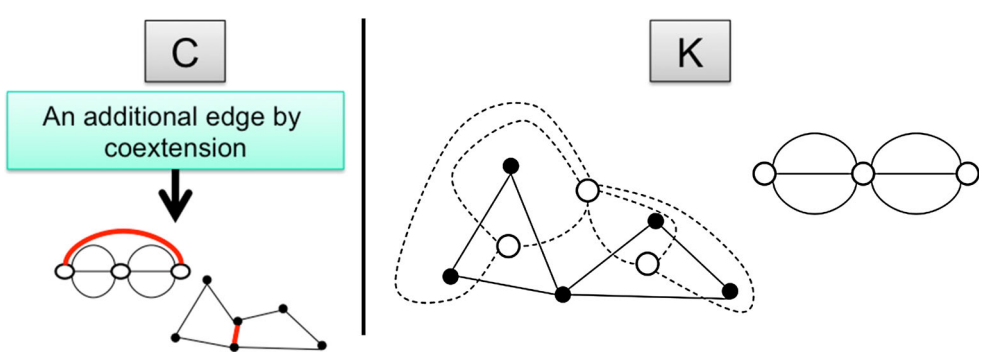



**Fig. 8** Coextension of a graph G

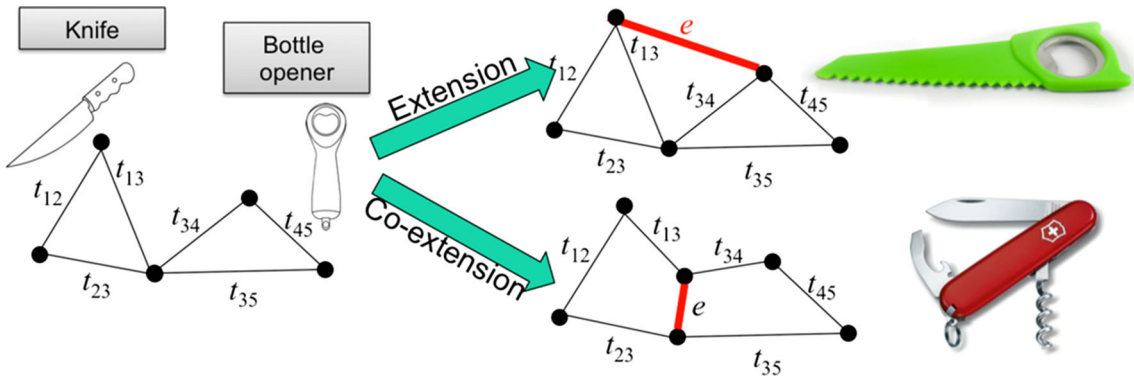



**Fig. 9** Illustration of the extension and coextension on one simple case

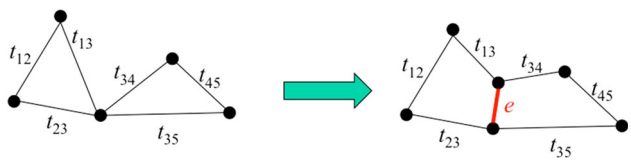



**Fig. 10** Coextensions of a graph G

system with the new technique and, even worse, it disturbs "old" working systems[2]! In the Fig. 10, the coextension transforms a working system $\{t_{12}, t_{13}, t_{23}\}$ into an independent set (hence no more a working system) and it is necessary to add $e$ to the system to make it work again. *The new technique is now required to make work systems that worked without it before! We could speak of value destruction.*

(c) The new edge connects connected components that were independent before, i.e. the new technique enables "bigger" working systems by aggregating smaller working systems. The new edge integrates known working systems into a bigger one. Strangely, enough the new, "bigger" working system does *not* contain the new edge! It enables to combine into one working system two previously known, but independent, working systems. This is the critical property of coextension: *it "combines" working systems*. As such it is *pervasive*.

(d) Working systems combination is "*modular*". For one "old" working system (say $\{t_{12}, t_{13}, t_{23}\}$), there are now two working systems alternatives: $\{t_{12}, t_{13}, t_{23}, e\}$ and $\{t_{12}, t_{13}, t_{34}, t_{45}, t_{53}, t_{32}\}$. It means that $\{e\}$ and $\{t_{34}, t_{45}, t_{53}, t_{32}\}$ are interchangeable from the point of view of $\{t_{12}, t_{13}, t_{23}\}$. *Hence coextension creates what engineering usually calls "platform" and "modularity".*

(e) Coextension increases the rank. As a consequence it opens new possibilities for extension.

**What is the design strategy in coextension? The concept: designing a generic technique.** With the elements given above, it appears that coextension consists in creating a relationship between (at least) two working systems to create a new working system that keeps all the properties of the aggregated systems (all previously known elementary techniques are present) and is modular. In C-K theory, the concept that corresponds to coextension is: *designing a technique that enables a working system that combines working systems that were independent until now*.

*Hence, we have shown that coextension in matroid exactly corresponds to the concept of the design of a generic technique, a technique designed to be generic to several, ex ante independent, working systems.*

Let's underline two surprising properties of the generic technique:

(a) As expected from a "generic technique", the new technique is *pervasive*, it has a *strong systemic impact*, and it combines working systems and enables "bigger" systems. But paradoxically it is *not* visible in the new working system! (e.g. in the figure above: $\{t_{12}, t_{13}, t_{34}, t_{45}, t_{53}, t_{32}\}$). The new technique is "hidden" by the new modules and platforms. It only appears when one shifts from one module to another. As we will confirm in the illustrations below: in steam engine history as well as in semiconductor techniques history, a generic technique is not a "big", new, breakthrough working system emerging out of nowhere—it is a discrete technique that helps combine existing working systems while changing them. It corresponds to a form of "creative destruction".

(b) Based on results from matroid theory, it is possible *to increase the number of independent working*

[2] We consider here co-extensions that are neither loops nor parallel edges in the dual.

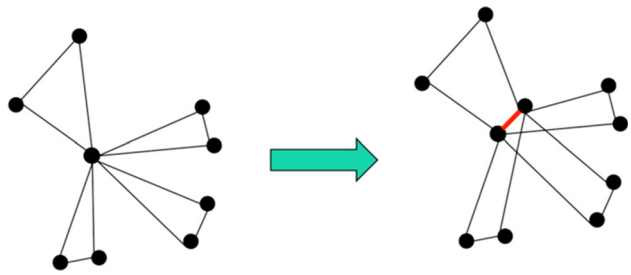


**Fig. 11** Designing a technique that is generic to four independent working systems

*systems combined by one new technique*. Hence the *genericity can be designed*. Genericity is not necessarily the result of the random aggregation of working systems. We show below one such generic technique (see Fig. 11).

### 3.3 Main conclusions on elementary operation in C-K/Ma

To conclude this part: we built a C-K model with matroid to study the endogenous dynamics of techniques. Note that this model meets the idempotency condition mentioned above: Matroid theory is kept stable by design in C-K/Ma. *This model enables us to considerably enrich the representation of this dynamics and the models of "combinations" in design:*

1. the model accounts for some critical distinctions in the design of techniques and technical systems.

   (a) it accounts for the *distinction between deduction and construction*. Deduction consists in proving that one working system (circuit) exists in the matroid; construction consists in creating techniques to design one new circuit (a new working system).
   (b) it accounts for the distinction between designing a "stand alone" working system based on existing technique (one "project") and designing a structured set of techniques: the first one consists in extracting one working system from the matroid of known techniques to create a stand alone working system—and we can show that it is possible for all the "minors" of the matroid; the latter consists in enriching the matroid of techniques.

2. the model clarifies critical distinctions that design theory makes between combinatorics and generativity. The model enlightens different forms of combinations, from non-generative combinatorics to generative combinatorics:

   (a) The identification of one circuit that already exists in a matroid corresponds to non-generative combinatorics
   (b) Designing one artefact from existing techniques, by deleting some interdependencies with other techniques corresponds to a (limited) generative combinatorics (some circuits are created that where not circuits in the initial matroid of techniques—but no new edges are created).
   (c) Extension consists in creating a new edge (new technique) to create a new working system, taking into account all interdependencies. This is a generative combinatorics: a new edge and a new working system are generated in the process. The new edge is actually dependent on the previously known one, and its design is driven by a concept of working system.
   (d) Coextension consists in creating a new edge that increases the dimension of the whole set of techniques, i.e. create new opportunities to invent new combinations. It is a higher level of generative combinatorics.

3. Regarding phenomenology: the model accounts for two basic, very different processes in the design of techniques, the design of pervasive or non-pervasive techniques:

   - *extension consists in designing one new working system in a non-pervasive way* (minimizing the systemic impact). It can be compared to the activity of an engineering department regularly designing new working systems in a cumulative way, avoiding the propagation of changes to all its elementary techniques.
   - *coextension consists in designing a generic technique enabling the* (*pervasive*) *combination of previously independent working systems*. It can aim at combining the maximum number of working systems, and hence, it aims at maximizing its genericity. It doesn't create "direct" value (the new technique is not involved in any new working system!), it is disturbing the "old" working system, and it recombines the working systems in a modular way.

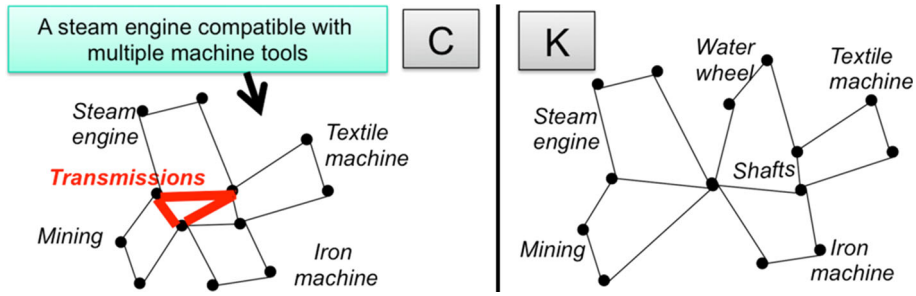



**Fig. 12** Designing steam engine as a generic technology

### 3.4 Historical illustration: the genericity of steam engine modelled with matroids

With the illustration below, we show how matroid models help to account for one famous historical case of designing a generic technology and how it confirms the most paradoxical properties of generic techniques modelled in matroids.

The story of the steam engine is often told this way: Watt designed a steam engine, and progressively many applications were found for it. Yet, as shown in (Dickinson 1936; Thurston 1878) and analysed in detail in (Kokshagina et al. 2012, 2013a), this story does *not* correspond to how Watt and Boulton designed a "generic" steam engine. We use C-K/Ma to enlighten some facet of this design.

In what follows we assume that the set of techniques Watt and Boulton were dealing with follows a matroid model.

The first generation of steam engines was adapted to mining, but not to other uses; hence, there was no "steam engine" in the 1770s, but only *water pumps for mining*—and Watt was first famous, in 1770s for greatly enhancing Newcomen *"fire pumps"* with a separate condensation chamber. Hence, in 1770 one can represent the matroid of techniques by the graph in K-space in Fig. 12. C-K/Ma predicts that the connected component of "fire pump" (i.e. steam engine + mining) and the connected component of machining (water wheel + textile machine + iron machining such as turning or drilling) can be connected in multiple ways but, basically, by two contrasted operations: extension or coextension. And the design of generic (pervasive) technique should be done by coextension. Hence, the hypothesis suggested by C-K/Ma: to obtain "generic steam engine", there has been coextension in the matroid of techniques—more precisely: Ha: there should have been an initial design brief that called for a coextension; Hb: one should recognize the technique designed by coextension through several features: almost invisible in the working system, rely mainly on pre-existing techniques and take full advantages of these pre-existing techniques.

Ha: history confirms that there was a brief for coextension. Actually the story of the "*generic* steam engine" begins in the 1780s, when Boulton asked Watt to work on a new concept "a steam engine that is compatible with multiple machine tools". And it is Watt's new design for this concept that appeared as the "steam-engine generic technology". Boulton's brief was targeting a complete recomposition of the structure of techniques of his time: if a steam engine is compatible with multiple machine tools, it becomes a core component of all future machines, as all new machine tools will be redesigned to take the best advantage of the steam engine (Fig. 13).

Hb: the newly designed technique exhibits traits of technique created by coextension: the design of Watt and Boulton led to a new order of techniques based on a new technique for movement transmission (the parallelogram on the figure above). The latter appears as a "*platform*" that connects the steam engine either to mining or to workshop machine tools (in textile or iron industry, etc.). The main design effort consisted in *designing the coupling technique* (here the double acting transmission system).

This new technique has the expected traits of a technique created by coextension (see Fig. 13):

- It doesn't emerge as a complete original technology—it actually relies on existing techniques.
- Despite its great systemic impact, the generic technique is discrete: the invention is neither in the fire engine, nor in the condensation chamber, it is only in the kinetic mechanism on top of the vertical rod.
- This is not an evolutionary process in which designers "discover" phenomena or "combine" randomly techniques: this is the intentional design of a pervasive technique (Hooge et al. 2014; Fig. 12).

Note that this example doesn't prove that the design of generic steam engine corresponds to a C-K/Ma model. It proves that there is no incompatibility between the model and the historical traces and it shows that applying this model enables to clarify that generic technology can be

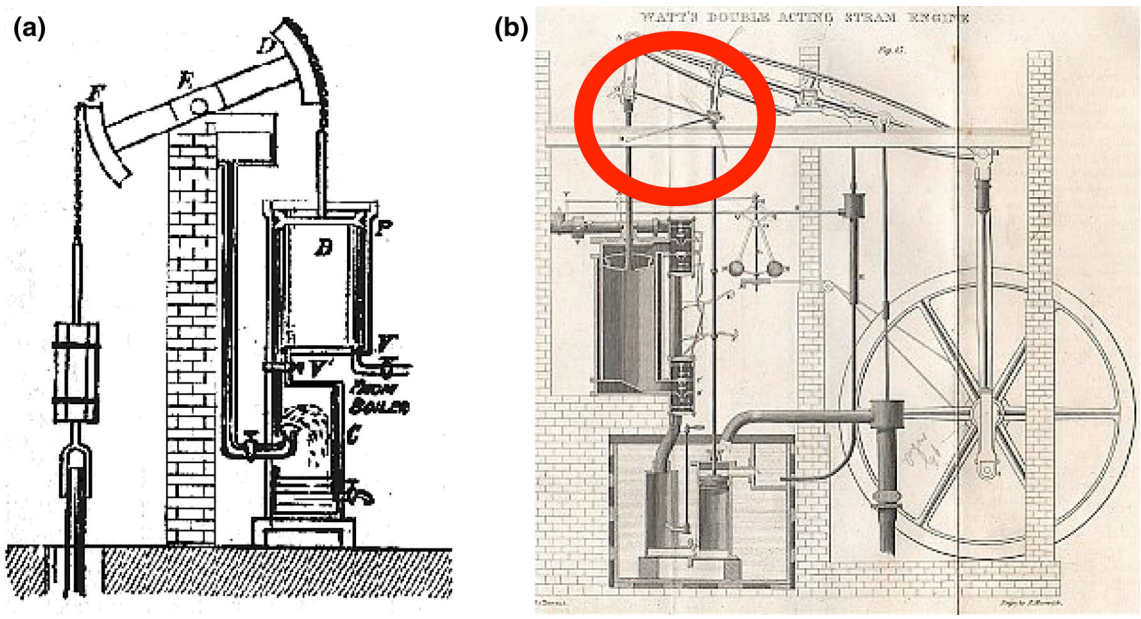



**Fig. 13** **a** 1763 Watt steam engine with separate condensation chamber (not generic); **b** 1784 Watt and Boulton Double acting steam engine. The parallelogram creates genericity

intentionally designed and is not necessarily following an evolutionary processes.

## 4 Towards a computational model of the dynamics of technologies

With CK/Ma, we have modelled elementary design operations related to the design of a technique in a set of techniques. Based on these elementary operations (deletion/contraction, extension and coextension), we can now analyse the dynamics of repeated design in a set of techniques by build quantifiers for critical features of a set of interdependent techniques (dependence, genericity, generativity) and modelling combined and iterated elementary operations. This will provide us with elements for a computational model of the dynamics of technologies.

### 4.1 Characterizing features of the dynamics of technologies

The matroid approach helps to quantify and characterize complex notions like independence level, generativity and genericity.

#### *4.1.1 Independence*

With C-K/Ma, we can first *quantify independence and dependence*: the rank of the matroid in K gives the level of independence; the co-rank gives the level of dependence (the level of dependence is also the independence in the dual, which actually corresponds to the independence between working systems). Both are linked by the equation: $r(M) + r(M^*) = |M|$ where $|M|$ is the number of edges, i.e. the number of elementary techniques.

Let's underline two special cases:

- "pure combination": In a Lego-like matroid ($U(1,n)$), the rank is one—all techniques are dependent on the others; it means that there is no "holes": no two independent techniques; the dual is $U(n-1,n)$, i.e. $n-1$ elementary working systems are necessary to "deduce" the last $n$th one. the systems are independent from each other.
- "perfectly decoupled engineering system": Let's consider now the $n$ techniques in a working system that follows the first axiom of Suh: the $n$ techniques form a circuit.[3] Now the first axiom applies "inside the working system", and any subset of $n$-1 techniques follow the first axiom. Hence the set of techniques enabling a Suh working system might be represented by a $U(n-1, n)$ matroid.

[3] Suh model can be directly translated in a matroid model, since it is based on vectors:

-In a DP-FR Suh matrix, one considers the DP-lines as vectors (of the FR-vector space); according to the first axiom, these vectors are independent.

-moreover, one should add one (implicit) DP: the system works. Hence a "validation" DP is "a (set of) instruments to test that the system works". This DP has a value on each FR: it validates each FR. In a system that follows the first axiom, this last DP depends on ALL above mentioned DPs.

Hence the U($n$, $n+1$) matroid (where n is the number of FR).

Now we also want to quantify the effect of independence level on generativity and genericity.

#### 4.1.2 Generativity

Generativity is a critical feature of any design theory (Hatchuel et al. 2011). It is usually hardly quantified. In C-K/Ma, it is possible to give a quantified evaluation of the generativity associated to a matroid $M$ and it depends on $M$ independence level (i.e. $M$ rank). Generativity can be seen as a quantification of the number of new edges (techniques) that can be created on a given matroid. We know now that they are two fundamental processes of single-edge creation—hence we can *quantify the generativity by the number of possibilities of single-edge extension* $g_{ext}(M)$ *and the number of possibilities of single-edge coextension* $g_{co\text{-}ext}(M)$ (*see figure below*). Note that these formulas are based on graphic matroids. Extensions (and coextensions) don't include the creation of parallel edges and loops in the matroid M (and in the dual of M).

(a) Generativity by (single-edge) extension: it is possible to evaluate the number of single-edge extensions that can be done on a given matroid of rank $r$ ($r(M(G)) = |V(G)| - 1$) and for $n = |V(G)|$ vertices. The maximal number of edges is $n.(n - 1)/2$ (this is the so-called *complete* matroid, where every vertex is linked by a single edge to any other vertex). If the matroid is simple (no loop, no parallel edges), there are already $|M| = r + r^*$ edges in the matroid (where r* is the corank, i.e. the rank of the dual of $M$); hence, the number of possible extensions for a simple matroid $M$ is

$$\mathbf{g_{ext}(M) = r.(r+1)/2 - |M| = r(r-1)/2 - r^*}.$$

If the matroid is not simple, then there are p loops or parallel edges; hence, the simple matroid associated to $M$ has $|M| - p$ edges and the number of possible extensions for a matroid $M$ with $p$ loops and parallel edges becomes

$$\mathbf{g_{ext}(M) = r.(r+1)/2 - (|M| - p) = r(r-1)/2 - r^* + p}.$$

This is one first measure of the number of "extensions" (i.e. cumulative, non-pervasive design of a new working system) with a given set of techniques. *This could be assimilated to the growth potential of an engineering department knowing the matroid of techniques M.*

2. *Generativity by* (*single-edge*) *coextension*: on the other hand, it is also possible to evaluate the maximal number of coextensions that can be made from a given graph of rank $r$, with $|M|$ edges. We have $g_{co\text{-}ext}(M) = r^*.(r^* - 1)/2 - r + p^*$ (where $p^*$ is the number of loops or parallel edges in the dual of $M$). *We estimate here the quantity of "generic" techniques that can be proposed on a set of given techniques*. Note that there is no reason to think that it is negligible.

#### 4.1.3 Genericity

With genericity we mean the number of applications *derived from one design* (Kokshagina et al. 2013a). *Genericity characterizes the systemic impact of one particular new technique*. In case of matroid, genericity can be modelled as the set of new circuits resulting from the design of a new edge $e$. We can characterize two contrasted forms of genericity (see Fig. 14):

(a) We count the *new circuits created* by the design of the new edge $e$. In extension, the new edge creates many new circuits, in the target flat and in all the flats containing it. In coextension, we need also to count all the circuits created by the design of $e$ and not involving $e$ directly. This genericity results from the new combinations between connected components of elementary techniques. Since a circuit is a working system and a working system can be considered as marketable, *this genericity can be assimilated to the "direct value" created by the new technique*.

(b) We can also count the new circuits that can *now* be created (after the design of $e$), with an additional effort—an extension effort or a coextension effort. In this case, this is *the "indirect value" or the "dynamic value"*. We call $M$ the initial matroid and $N$ the matroid created by $e$ added to $M$. We will use the generativity quantification constructed above. Note that in extension and in coextension the number of loops and parallel edges is unchanged, i.e. $p(N) = p(M)$ and $p^*(N) = p^*(M)$. For the edge $e$ we compute extension-genericity: $gen_{ext}(e) = g_{ext}(N)\text{-}g_{ext}(M)$ (and we can conversely compute: $gen_{co\text{-}ext}(e) = g_{co\text{-}ext}(N)\text{-}g_{co\text{-}ext}(M)$). We distinguish two cases:

- If $e$ results from an extension, then we know that $r(N) = r(M)$ and $r^*(N) = r^*(M) + 1$. Hence the extension generativity has decreased by $-1$ with the design of e by extension $\mathbf{gen_{ext}(e_{ext}) = -1}$. (Similarly $gen_{co\text{-}ext}(e_{co\text{-}ext}) = -1$). It just means that the number of possible extensions decreases (by $-1$) after each extension.
- If $e$ results from a coextension, then we know that $r(N) = r(M) + 1$ and $r^*(N) = r^*(M)$. Hence,

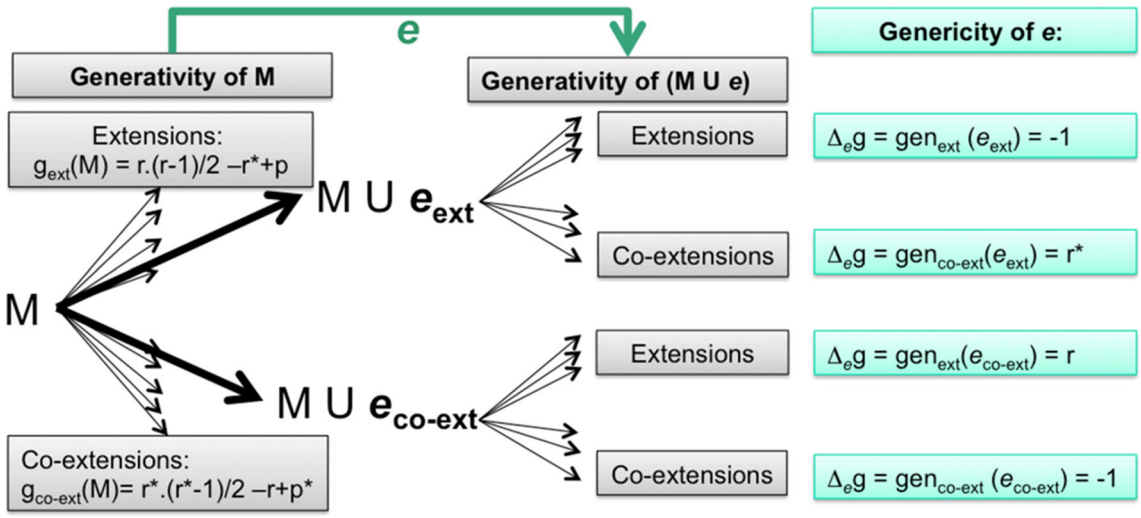



**Fig. 14** Generativity of a matroid, genericity of a new edge added to this matroid

$$gen_{ext}(e_{\text{co-ext}}) = (r+1)r/2 - r^* + p - [r(r-1)/2 - r^* + p],$$

i.e. $\mathbf{gen_{ext}}(\mathbf{e_{co-ext}}) = \mathbf{r}$ (conversely: $gen_{\text{co-ext}}(e_{ext}) = r^*$). *The extension-genericity of e created by coextension is approximately r*. Conversely, the coextension genericity of e created by extension is approximately $r^*$. It means that the number of possible extensions increases (by $+r$) after each coextension.

#### 4.1.4 Combining multiple elementary operations

Now that we have elementary operations (deletion-contraction, extension and coextension) and quantifiers for elementary operations, we can model combinations of elementary operations. We give an illustration in Fig. 15.

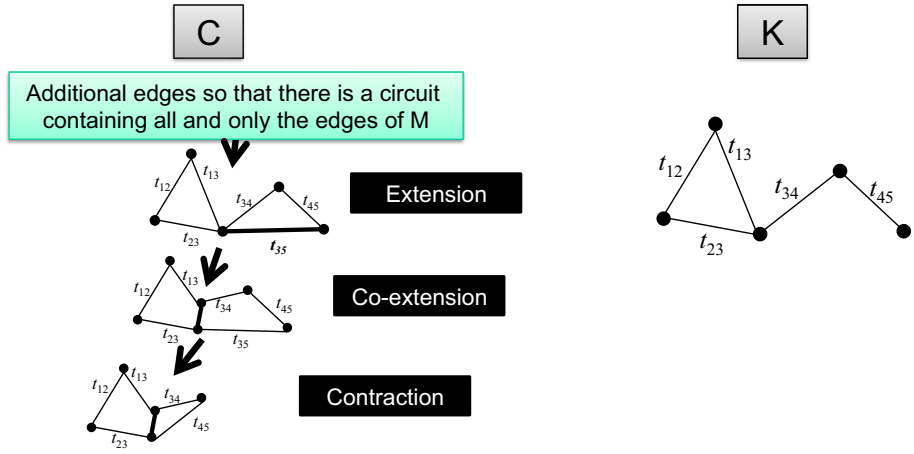
### 4.2 Illustration: designing generic technologies in the semiconductor industry

We use these quantifiers to analyse the design of generic technique in semiconductor industry. It is presented in more detail in (Kokshagina et al. 2013b). It can be schematically described as follows: there are semiconductors systems that integrate radio signals (radar, wifi, etc.) and computing power, but these systems are poorly integrated and neither use high level radio frequency sensors nor powerful computing power. The concept consists in combining three, initially unrelated, technological families:

- Family 1: the computing elementary techniques (elementary techniques for the so-called CMOS transistor).
- Family 2: the Radio-Frequence sensors, able to receive and digitalize radio frequency signals, these RF system being based on bipolar technologies.
- Family 3: the so-called "back-end" system, the elementary techniques basically in charge of routing and processing signals.

The concept is: "a matroid of elementary techniques that combine the three technological families". By combination, one expects a system that enables circuits using elementary techniques in the three technological sub-systems (computing, RF and back-end) and circuits using elementary techniques in every pair of the three technological sub-systems (RF and computing; RF and back-end, computing and back-end). The notion of "combination" is usually quite fuzzy and hides the design issues. Applying the matroid model enables to clarify several contrasted alternatives with different "values". Relying on extensions and coextensions, one can propose four different solutions (see below) and evaluate their potential in term of *generativity* and hence *compare the genericity created by each design alternative*.

- The "pure extension" appears as an effort *to design "micro-combinations" of elementary techniques*; it brings multiple working system—hence a direct value—and still none of these systems enables to combine *all* previously known elementary techniques. The genericity is negative: it means that the new design has decreased the generativity potential of the matroid.
- The "pure coextension" is a generic technology that creates a working system that uses all previously




| | r | r* | $g_{ext}$ | $g_{co\text{-}ext}$ | $gen_{ext}$ |
|---|---|---|---|---|---|
| Initial K | 4 | 1 | 5 | 0 | |
| After extension | 4 | 2 | 4 | 1 | -1 |
| After co-extension | 5 | 2 | 6 | 0 | +2 |
| After contraction | 4 | 2 | 3 | 0 | -3 |

**Fig. 15** Design process combining elementary matroid design operations—evolution of the quantifiers of the set of techniques

known elementary techniques; moreover, it is modular (pairwise combinations are also possible). Hence there is a direct value here also—but the number of newly created working systems in coextension is rather lower than in "pure extension" case. The genericity is positive: the new design has (strongly) increased the generativity potential of the matroid.

- Hybrid case 1 is also an interesting design strategy: it exhibits a new connected sub-component that connects each of the modular ones. We see here a "*platform*". Genericity is relatively high.
- Hybrid case 2 enables to get the expected performance (connections between the connected components), but it does so *by designing only two edges*, whereas all the other solutions design three edges. This is a particularly efficient "generic" technology.

The design strategy adopted at STMicroelectronics to develop the new technique actually follows that latter process: mixing sub-technologies of CMOS and bipolar into a new connected component called bi-CMOS (hence an extension) and the redesign of the back-end to connect it to the new bi-CMOS (Fig. 16).

This example shows how the C-K/Ma enriches our understanding of the design of techniques with systemic impact, supported also with quantitative criteria on generativity of the new matroids and genericity of the designed technique.

More generally, one can see on this example how computational models could be developed to simulate the possible combinations of extensions and coextensions to modify a set of interdependent techniques—this is, however, out of the scope of this paper.

### 4.3 Characterizing the dynamics of techniques

With C-K/Ma, one can at least characterize specific laws of the dynamics of techniques. Note that until now, all results are obtained for any matroid (even if we illustrated mainly with graphic matroids). In what follows, we will also use other specific type of matroid, namely uniform matroid.

#### *4.3.1 Result 1: Lego-like structure of techniques are locked and evolve only through exogenous dynamics*

Let's analyse the "intuitive" model of "combination of techniques" (used for instance in Arthur 2009). In this model, each elementary technique can be combined with another one to create a working system—hence we called it the "lego-like" structure.

Depending on the type of relation we analyse, there are two types of analysis possible: either one considers the graphic matroid $G_n$ associated to Lego-like structure (this is a dipole with n edges). In that case, we have (self-evidently): $g_{ext}(G_n) = 0$: extension is impossible in $G_n$. *This system is "locked" for extension*. The pure combination approach prevents the design of new working systems! (actually because all working systems obtained by combinations are considered as known in the lego-like structure—i.e. any working system, i.e. any circuit linking

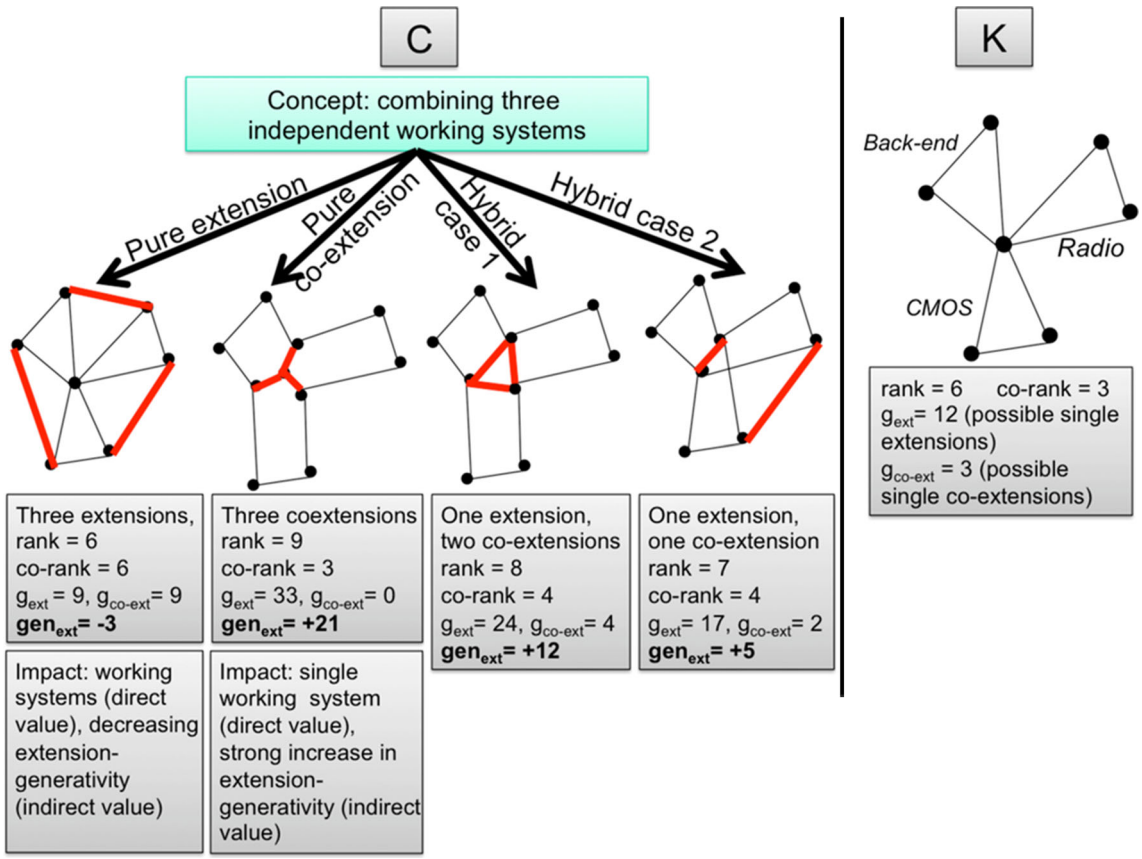



**Fig. 16** Combining technologies—the case of B9MW in semiconductors

techniques from $G_n$ can be obtained by deletion-contraction).

Still we can compute:

$$g_{\text{co-ext}}(G_n) = (n-1).(n-2)/2 - 1.$$

Hence $U(1,n)$ is very generative in *coextension*. However, these coextensions are hardly visible in "lego-like" approaches *because the co-extended matroid is no more Lego-like* (the $G_n$ family is not stable by coextension).

Another analysis is based on the fact that the lego-like structure can be seen as the matroid $U(1, n)$. One can now examine the dynamics of this specific family of techniques by considering the $U(n, p)$ family. Note that it is an interesting case for the matroid model since the $U(n, p)$ matroid is, generally speaking, not graphic so the study of $U(p, n)$ types shows how the matroid model applies beyond graphic matroids. To help the reader: the $U(p, n)$ family is defined over a set of n elements and a subset of elements is independent if and only if it contains at most p elements. A subset is a circuit if it has exactly $p + 1$ elements. It can be represented as the matroid of linearly independent subsets of n vectors in general position (i.e. "general case", no special, coincidental cases) in an $(p + 1)$-dimensional real vector space.

As known from matroid theory (and this is quite self-evident), the one-element extension of $U(1, n+1)$ is $U(1, n + 1)$. It consists in adding one building block that is combinable with all previously known building blocks. A coextension is an extension in the dual. And the dual of $U(p, n)$ is $U(n - p, n)$. Hence the one-element co-extended matroid is $U(p + 1, n + 1)$. The co-extended Lego-like structure is hence $U(2, n + 1)$. It means that the Lego-like structure seen as a matroid $U(1, n)$ is not stable by coextension. Note that $U(2, n + 1)$ is not graphic.

In both models, we see that *a pure Lego-like model of the dynamics of technologies won't be able to account for technological dynamics based on coextension. Hence, a Lego-like structure cannot account for the endogenous dynamics of technological systems.* That is why "pure combination" models tend to rely on exogenous dynamics like new science (Arthur 2009).

#### 4.3.2 *Result 2: A structure of purely independent techniques implies exogenous dynamics*

In the case of an "ideal" engineering system following Suh axiom, we showed above that this system might be

represented by an n-edge cycle graph, $C_n$, which is also the $U(n-1, n)$ matroid.

One can interpret this "configuration of technologies" either as an evolution of the n-edge cycle graph or an evolution of $U(n-1, n)$.

The reader will easily be convinced that in the graphic representation $C_n$, there are many possible extensions but all of them "break" the cycle, hence the family $C_n$ is not stable by extension. The matroid is no more following Suh axiom.

This is strictly similar with $U(n-1, n)$: by extension it becomes $U(n-1, n+1)$, which is no more of the type $U(k, k-1)$ where $k$ is a positive integer. Note again here that $U(n-1, n+1)$ is not a graphic matroid.

This corresponds to the fact that *Suh's first axiom has a hidden effect: it prevents the design of multi-functional techniques*.

More generally, in system engineering one tends to favour systems with independent techniques—for instance, one will tend to separate mechanical, thermic, chemical or biological processes in a complex system (like a boat or a process machine). Interdependences are rather seen as defects, e.g. chemical corrosion of mechanical parts in a boat. *Hence any "perfect" system engineering will finally prevent the emergence of a multi-functional technique*!

Hence, the two simplified representations of technical systems—pure combination or pure independence—actually correspond to very particular matroids and they are actually representations that cannot account for the endogenous dynamics of techniques.

#### *4.3.3 A necessary condition for the continuous endogenous dynamics: the combination of extension and coextension*

We have shown that *extensions or coextensions, enabled alone, lead to deadlocked systems since the genericity of extension and coextension is negative* (we might have here an explanation for the "blocked technical systems" described by the historian Bertrand Gilles (Gilles 1986).

*A direct consequence of this negative genericity is that the only way to get an unlocked endogenous dynamics consists in combining extension and coextension—i.e. the combination of the design of working systems and the design of generic techniques.*

This combination can lead to several types of dynamics: two special regimes can be easily modelled that fit with existing engineering domains:

- The "*extension-driven" regime* gives priority to extension (the design of working systems). In this regime, coextensions (the design of generic techniques) are as rare as possible. Over time, the matroid becomes saturated and no extension is possible anymore. Hence, one coextension is required, it increases the rank by +1 (the rank becomes $r+1$) and the generativity by $+r$. Over time, the rank increases slowly: one coextension that increases the generativity by $r$ and the rank with +1, then $r$ extensions until generativity decreases to 0 and again coextension, this time with the rank $r+1$, etc. The corank $r^*$ increases with +1 for each extension, hence it increases a lot. Over time r becomes relatively low compared to $r^*$. There are finally a hand of independent techniques in a world of independent working systems. *We can recognize here the technical dynamics of automotive or aeronautic industry in the mechatronics era.*
- Conversely, the "*coextension-driven*" regime favours coextensions. We have then a symmetrical situation: a hand of independent systems and many independent techniques—but among them there are "generic" techniques that re-organize around themselves the working systems. We recognize *here the technical dynamics of semiconductor industry*.

### 4.4 Revisiting patent data: an illustration of the C-K/Ma dynamics of techniques

There is an open-ended debate in the analysis of the dynamics of techniques and inventions: is the source of technological novelty related to new combinations or is it related to a pure origination, with few antecedents to originate the new technological pathway? What are the relative roles of combinations and originations? (for a recent contribution to this debate see: (Strumsky and Lobo 2015)). Our model provides new answers:

1. we should necessarily find both types
2. in an "extension oriented" regime (i.e. a regime where the design favours the design of working systems), we can predict a clear dominance of combination and limited generativity. Actually, in an extreme extension-driven regime (all extensions are designed before a new coextension is done), $x$ coextensions enable approximately $x^2$ extensions. 1000 coextensions would enable 1000000 extensions. These hypotheses are confirmed by the most recent quantitative study of patents (Strumsky and Lobo 2015): this study identifies the category of "origination" patents (that corresponds to coextensions) and categories for combination (that correspond to extensions). It shows an overwhelming dominance of combination, and the relationship between cumulated coextensions patent and cumulated extension patents shows a power relationship, with a power between 1 and 2, meaning that patents correspond to an extension-driven regime, still not the most

extreme one (not all extensions are patented before one coextension appears!).

## 5 Main findings and conclusion

In this paper, we studied the design of techniques and its effect on a set of existing techniques—an effect that can be as non-pervasive as possible or as pervasive as possible. We built a model of the design of knowledge structure by combining one design theory (C-K theory) and a model of interdependences in knowledge structures (matroid theory). This C-K/Ma model brought us following findings:

1. C-K/Ma accounts for *basic phenomena in the design of pervasive and non-pervasive techniques*. In particular, C-K/MA *helps understanding the phenomenology of generic techniques* such as:

   (a) A generic technique—like the kinetic parallelogram in steam engine—does not seem to add functional value to the system (the steam engine and the machine tools were known and did not require a cinetic parallelogram to work!) but is finally in every machines (because this is the key technique to combine the two previously independent working systems);
   (b) A generic technique couples and decouples; it creates a "modular" relations between working systems—it reorganizes technical system in a flexible way.
   (c) A generic technique appears first as just coupling two systems without adding direct value—but it has a strong "indirect value", as many new techniques can then be added to the newly coupled working systems.

2. C-K/Ma, when applied iteratively, helps to propose *new laws for the dynamics of techniques and helps to build strategic alternatives in the design of techniques*. In particular:

   a. We show that, in an iterative perspective, an endogenous dynamics would necessarily rely on extension and coextension (i.e. the design of working system and the design of generic techniques) (otherwise the dynamics would stop). It seems that historical cases (like the industries of the twentieth century) tend to rely mainly on extension processes—with rare coextensions, i.e. few generic techniques—and still it is possible to describe theoretical trajectories with regular coextensions. The model confirms also quantitative empirical works on the source of technological novelty in patents.
   b. C-K/Ma offers a guide for the design of technologies with systemic impact, based on generativity and genericity criteria. C-K/Ma uncovers a large variety of design strategies for pervasive techniques and provides criteria to evaluate how these techniques change the generativity and the genericity of the newly created technical system.

Moreover, C-K/Ma contributes to design theory since it provides some basic quantifiers and operations that could lead to a *computational* model of the process of designing techniques with systemic impact. In particular:

(a) In C-K/Ma, one can characterize main operations (extension, coextension, etc.) and their quantified effect (rank, co-rank, generativity, genericity).
(b) In C-K/Ma, one can clarify the complex relationship between combinatorics and generativity, from non-generative combinatorics (identify circuits that already exist in a matroid) to generative one (generativity by extension, that results from the combination of independent techniques in the matroid of techniques and generativity by coextension, that results from the combination of independent systems in the dual of the matroid of techniques).
(c) The model also enables to understand the limits of "intuitive" models of techniques. In particular, we show that the usual "lego-like" combinative models prevent to analyse the endogenous dynamics of technical systems. And we also show that the alternative "independence-driven" model is also limited: in engineering design, the "ideal" system maximizes independences (following Suh's first axiom) and this system prevents the design of a generic technique. This means that if one represents an engineering system with independent techniques, then it is impossible to represent the design of a generic technique in such a model.

Regarding computationaly, one has, however, to remind that matroids, in general, are not an easy object for computing. As often in model and computationability, algorithms are often more efficient when implemented at the level of specific models (vector matroid, graphic matroid, etc.). Still the logic of computationability at matroid level also helps to get very general models on the computational complexity of matroid models:

(a) on the one hand, it is proven the efficiency of algorithms that rely on the so-called "matroid oracles" or, more specifically, on "independence oracle" i.e. these algorithms take an oracle as input

(i.e. a subroutine that tests whether a subset of elements is independent), and it is proven that they work on the variety of objects that follow the matroid axioms—this is the case for the famous greedy algorithm.

(b) on the other hand, these formalisms were useful to prove that certain matroid problems can't be solved in polynomial time—for instance: testing whether a matroid is uniform. It might explain why it is so hard to work, at a very general level, on independence structures. It also illustrates the challenges that design science will have to face in the future.

It is important to remind that the results are obtained under the assumption that the set of techniques follows the "independence augmentation" axiom. Accepting this assumption enabled us to formulate hypotheses on the design of one technique and its impact on a set of technique and to formulate hypotheses on the dynamics of techniques. Moreover, we have shown on some empirical cases that these hypotheses are note rejected. Still this calls for further research that would help to confirm or reject the "independence augmentation" assumption and that would also help to discover new properties of C-K/Ma and test them.

Finally, relying on advanced models of design theory and matroid, this paper strengthens the study of the endogenous dynamics of technical systems and opens new ways. Beyond the phenomena and the strategy, the model might also be useful to study economics and organizational issues. In particular, the logic of "indirect" value in the design of generic technology actually raises interesting institutional issues: are companies—more interested for direct value—able to design generic technologies with high indirect value? Who could be the new actors in charge of these designs? To study the design of generic techniques, we integrated in the model the logics of cohesion and interdependences between techniques—this might now lead us to shed new light on the logics of cohesion and interdependences in economics and society.

## Appendix: Definition and principles of the main notions of matroid theory used in the paper

| Matroid theory | Matroid of techniques |
|---|---|
| Matroid: an ordered pair $(E, I)$, where $E$ is a finite set, and $I$ is a collection of subsets of $E$ (which can be called the independent set of (E, I)), where I satisfies the following properties: | Elementary techniques are the elements of the matroid<br>Working systems are the dependent set of the matroid. They are supposed to follow matroid conditions |
| (1) $I$ is non-empty;<br>(2) every subset of every member of $I$ is also in $I$ (hereditary condition);<br>(3) if $X$ and $Y$ are in $I$ and $\lvert X\rvert = \lvert Y\rvert + 1$, then there is an element $x$ in $X$–$Y$ such that $Y \cup \{x\}$ is in $I$ (independence augmentation condition) | A working system is elementary if it can't be obtained by merging two smaller systems |
| Circuit: a subset of $E$ that is a minimal dependent set (removing any one element of the circuit transforms it into an independent set | A minimal working system (if a technique is removed, the working system doesn't work) |
| Base (or basis): a subset of $E$ that is a maximal independent set (adding any one element to the base transforms it into a dependent set) | A set of independent techniques |
| Rank: corresponds to the highest size of an independent set (the size of any base) | The highest number of independent techniques |
| Dual of matroid: the matroid M* formed on the same set of elements E but the bases of the duals are the complementary elements of the bases of M | Correspond to the relations between elementary working systems |
| Deletion (of one single element): given a matroid $M = (E, I)$ and an element e of $M$, deletion is the operation that forms the matroid $M\backslash e$ by removing $e$ from $E$ and keeping the independent sets of $I$ that are included in $E$-$e$ | Removing one technique |
| Contraction (of one element): a deletion in the dual $M^*$ of $M$. In a graphic matroid: merge two vertices linked by an edge; in a vector matroid: contraction corresponds to projection along the single element | |
| Extension: the operation that forms the matroid $N$ by adding $e$ to $M$ such that $N\backslash e = M$, i.e. $M$ is the matroid resulting from the deletion of $e$ | As shown in part 2: designing a non-pervasive technique |
| Coextension: an extension in the dual of M | Designing a pervasive technique (generic technique (see part 2) |
| A flat: a flat $F$ is a set of elements of $E$ such that it is impossible to add a new element of $E$ into $F$ without changing its rank | A set of elementary techniques that are incompatible with any other elementary technique outside the set |
| Connected component (2-connectedness) in a matroid M: is a matroid $N$ of $M$ such that for every pair of distinct elements of N, there is a circuit containing both | |

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**Proceedings of DETC '97**
**1997 ASME Design Engineering Technical Conference**
**September 14-17, 1997, Sacramento, California**

**DETC97/DTM-3873**

# THE *N*-DIM APPROACH TO CREATING DESIGN SUPPORT SYSTEMS

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## ABSTRACT

Creating practical design support systems is a complex design endeavor. We approach it with an evolutionary process, one that studies the design information flow then builds and tests information management support systems. Through our experience with industrial partners we have evolved this process into a set of methods and tools that support these methods. We have evolved an infrastructure called *n*-dim, that is composed of a small number of building blocks that can be composed in ways that match the complexity of design contexts and work. We have developed this infrastructure to be highly flexible so as to allow us to conduct this evolutionary process in a practical project setting.

## INTRODUCTION

Our approach to creating design support systems is influenced by several well documented observations regarding the nature of modern engineering design. In this paper, we motivate our approach based on a considerable body of empirical work and on the exigencies of supporting engineering design practice. Our argument is that an engineer's work is characterized by features which make the design information very complex. The goal in supporting such work, then, is to help the engineer tame this complexity. This requires, in turn, a support system that is capable of representing the information in all its complexities and is comprehensible, usable, and maintainable. Of course, one must also be able to build the environment within a reasonable time frame and budget.

In order to achieve this goal, we iteratively apply the following steps: study the design work, develop systems to support the work, and evaluate these systems by studying the new work environment after system deployment. While these steps are almost obvious, carrying them out under pragmatic conditions can be extremely difficult. In order to achieve and sustain the ability to intervene in a workplace and improve design practice in an organization, we need tools, methods for applying them, and a general philosophy that guides the process. Furthermore the philosophy, methods, and tools need to be internally consistent[1]. Our approach consists of a diverse set of tools and methods borrowed from a wide range of disciplines as required by the context being studied and an over-arching philosophy that guides in selecting the right tools and methods for each work context. We have used this approach in several industrial and academic contexts and the results reinforce our claim of this approach's value in supporting engineering design.

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1. In order to iterate this process in a reasonably efficient manner, we must have a computational infrastructure that supports such iterations by, for example, supporting easy scripting and testing with throw-away code.

**Table 1: Our experience in studies of engineering design**

| *Design Project* | *Methods Employed* | *Focus* |
|---|---|---|
| Process Control system design (Westinghouse) | Direct observation of design meetings; collection of all design documents; recording meetings. | Preliminary design. |
| Integration of Material Databases (ALCOA) | Tracking information flows with a survey. Creating concept structures using semi-structured interviews. | Information sharing across divisions to reduce duplicated work. |
| CINERG: Multi-University Collaborative Distributed Design | Direct participation and observation. Analysis of documents and messages exchanged.<br>Post hoc review. | Feasibility of electronic collaboration in asynchronous, distributed design with periodic face-to face meetings and conference calls. |
| Design of and manufacture of electric power devices (multiple studies) | Questionnaire and direct interviews with participants in all phases of the design manufacture and services. Analysis of critical documents. | Information need and flows in the design and manufacturing process (intra-project and inter-project flows). |
| Undergraduate project courses in software engineering | Analysis of design information including intermediate and final products and electronic communications among designers. | The effect of communication on outcome. |

The outline of the paper is as follows. The first section, "The Nature of Engineering Work," discusses our understanding of engineering design as derived from empirical studies and documented observations. It highlights the complex heterogeneous context of design and the variety of information management activities that comprise engineering work. The next section, "Addressing Information Management," contends that, in order to address the complexity of design contexts, one has to match it with a corresponding variety of building blocks and ways to connect them. "*n*-dim: An Infrastructure for Information Modeling and Applications" discusses our approach to identifying these building blocks and an infrastructure called *n*-dim within which they can be composed (Levy et al., 1993). This section also reviews some basic features of *n*-dim, the continuously evolving infrastructure for developing design support systems. "How *n*-dim Addresses a Variety of Information Activities" illustrates how *n*-dim's features and some applications we have developed address the complexity of engineering design contexts and work.

## THE NATURE OF ENGINEERING WORK

In order to understand the nature of engineering work as it is actually carried out in day to day practice, we present some of the more important findings from empirical observations of real design situations. This is followed by a brief discussion of the increasingly distributed and varied contexts within which design takes place. We can draw some conclusions regarding the nature of systems required to adequately support design activities in practical contexts.

### Empirical Studies of Design

Empirical Studies in engineering design span a variety of objectives, use a diversity of methods and focus at different levels of granularity (Clark and Fujimoto, 1991; Hales, 1987; Kuffner and Ullman, 1991; Leifer, 1991; Subrahmanian 1992; Tang, 1989; Wilkins et al., 1989). They range from comprehensive product development studies (Clark and Fujimoto, 1991; Hales, 1987) to studies of individual designers (Bucciarelli, 1984). These studies provide a tapestry of design covering the organization of design, the evaluation of normative methods in design, group work around a table, information flow analysis, process-based analysis, and task-related analysis for cooperating groups. In this section, we briefly describe studies of design conducted by us which define and affirm our approach. Table 1 presents summaries of the design process studies we conducted or in which we participated. These studies approached design from different perspectives and employed a variety of methods to gather and analyze data. This diversity enables us to obtain a relatively comprehensive understanding of the design process. Drawing upon these studies and on those of others, we present below some key findings.

- The initial design phase is characterized by the creation of an information base.
- Engineers spend a considerable amount of time in seeking, organizing, modifying, and translating information relevant to their design work (which often transcends the engineer's personal discipline). While specific percentages might vary in different contexts, 75% appears to be a reasonable estimate (Engelmore and Tenenbaum, 1990).

- Design is a social and linguistic process requiring the participants to actively negotiate and translate information from one object world into other object worlds each being a composite based on the training, background, experiences (general and specific), etc. of each individual participant (Bucciarelli, 1984). There are difficulties in synthesizing and organizing diverse information into a coherent view.
- Due to the lack of adequate information integration, designers often evaluate only a single alternative.
- The organizational structure of the design team and the institution constrains information integration.
- The media used are inadequate to capture the required level of richness of the information.
- Even in the more analytical side of an engineer's work, the non-formal, non-analytic, tacit information about an analytic step is an important piece of the design information (Subrahmanian et al., 1993b). For our purposes, the significant thing about this is that even in the core of traditional engineering work, the role of translation, annotation, clarification, etc. is of central importance to the substance of an engineers task.
- Design history and rationale are continually being lost. This loss can result in the need to recreate the rationale of a design. This reverse engineering process can lead to repeating the same mistakes and failures encountered during the original design process. The central problem here is that the information required to learn from the past is either not captured or is so poorly organized and documented that its retrieval and value is compromised (Petroski, 1989). It is estimated that less than 20% of the intellectual capital of any firm is re-used.
- Design knowledge evolves since it is composed of a relatively stable core of knowledge surrounded by a much more unstable, rapidly changing periphery (which might later become part of the core).
- The relative size of the stable core with respect to the unstable periphery is a function of the maturity of the constituent disciplines.
- History maintenance for product classes plays an important role in an organization's ability to recoup on its investments in design knowledge.
- When the organization and/or the process is documented by the designers, it is often inaccurate and obsolete.
- The preliminary design phase is chaotic with the identification and definition of the required structures (design processes and organizations) being part of this phase. Engineers spend a significant part of their time coordinating, scheduling, inter-relating, and reconciling their work with others.
- There are multiple perspectives on and terminological differences in design information.
- Computational models and tools are distributed among different groups.
- The tools used impose limitations on effective collaboration.
- Design groups change over project lifetimes in structure and composition.
- There is, often, a mismatch between who has the information and who is assigned the specific design task.
- Communication characteristics (e.g., number of integration channels, communication infrastructure) has an impact on outcome.
- Functions of communication patterns (e.g., terminology used, volume of information exchanged) can be used as indicators of future design outcomes.

In summary, one cannot separate "pure" engineering work (in the sense of creating models, solving equations, etc.) from information management activities (IMA). Given the disproportionate time allocated to IMA in most engineering work, supporting IMA (computational or institutional) takes on considerable urgency. In order to understand what is entailed in providing such support, we can re-phrase the above findings at a higher level of abstraction: Engineers continually and collaboratively carry out their work by manipulating information required to solve the design problem at hand. It is also of considerable importance that engineers be able to build upon and draw from the collective knowledge of the organization thereby enabling its reuse and improving design performance (e.g. lower cost, less time, fewer errors, etc.). In our studies of the current procedures in engineering information management in several industrial organizations, we have discovered the following information integration activities and needs.

**Information manipulation** is characterized by three sets of activities. The first set is the creation, retrieval, classification, and evaluation of information. Supporting these activities requires functional support for creating, structuring, and finding information, and the use of standards. The second set is the transformation and translation of information across multiple representational structures. Supporting these activities requires functional support for sharing methods and tools, use of standards, integrating legacy methods and tools and external methods and tools, and the ability to evolve the system. The third set is the storage, access, and protection of information. Supporting these activities requires functional support for distributed storage and replication, access control, and security from external damage.

**Knowledge building** is characterized by two sets of activities. The first set is the capture and re-use of the design process and the design rationale. It requires support for capturing history,

capturing rationale, and structuring information. The second set of activities is the capture, consolidation, and re-use of knowledge (generated from the previous set of activities) by designers with different perspectives. Supporting these activities requires functional support for learning by induction, enabling end user customizing, and sharing information. Collaboration comprises the activities of negotiation and coordination that require support for sharing information, change management, and work flow and process tracking.

### The Context of Engineering Work

From these observations and the published literature, we can characterize the context within which engineering work (including, of course, IMA) takes place and some of the issues that need to be addressed by support tools. In what follows, we describe several of these characteristics. An extended list with the consequences of creating design support systems can be found elsewhere (Reich et al., 1996b)

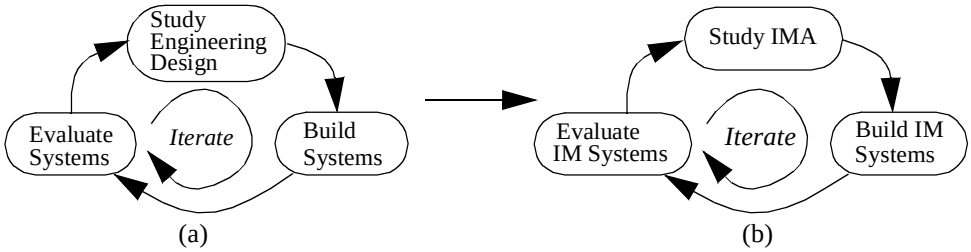
1. *Extended time*. Engineering activities extend over potentially long periods of time. The context of design must be maintained over that period and longer to allow for future reuse and for addressing life cycle issues.
2. *Multiple places*. Engineering activities take place in multiple locations which may change over time.
3. *Multiple cultures, practices, and behaviors*. Engineers participating in design projects come from different cultures. Organizations, through their development, evolve distinct cultures consisting of different practices, policies, and behaviors.
4. *Multiple languages*. People from the same discipline but from different organizational departments or divisions often use different languages or terminologies to describe disciplinary knowledge (Sargent et al., 1992). People themselves also use different languages (informal, e.g., text, images, audio, video; or formal, e.g., equations, 3D models) to refer to different perspectives of the same objects (Subrahmanian et al., 1993b).
5. *Multiple tools*. Some tasks, such as word processing, can be accomplished using different tools or methods. The use of different tools for the same tasks occurs in the same organization and certainly occurs in different organizations that work together. Moreover, existing organizations have significant investments in legacy tools that must be integrated into new computational environments.
6. *Multiple areas of expertise, disciplines, or tasks*. Engineering engages people with multiple areas of expertise in one discipline (vertical integration) as well as experts from multiple disciplines (horizontal integration) (Konda et al., 1992).
7. *Multiple perspectives*. People with the same area of expertise or from the same discipline may have different perspectives about a particular project if they assume different roles in the collaborative effort. One person can sometimes act as a customer and in other cases as a developer. Perspectives evolve or are determined in response to the context of a particular project.
8. *Interchangeable interaction methods*. A tool must support different anytime anyplace interaction methods in the same environment with the ability to switch back and forth between these methods.
9. *Usability and adaptability to workers with different levels of computer-literacy*. Of the tools desinged to support collaboration that are described in the literature, a large number are developed for use by experts who are proficient in the use of computers. More importantly, the people developing these tools may not appreciate the difficulties that regular users may have. In real engineering work, no assumption about the design participant's (customers as well as designers) computer proficiency can be made.

Based on these observations, we are led to the conclusion that much of the difficulty in doing design lies in acquiring, manipulating, transforming, using, and storing information in multiple and varied contexts in a manner suitable for subsequent re-use. These factors results in a situation characterized by a great deal of complexity and variety. As Ashby (1958) points out, a "control system" for such a situation, if it is to be adequate to the task, must exhibit at least as much complexity and variety. In the next section we explain how we approach the problem of providing support in the face of such complexity.

## ADDRESSING INFORMATION MANAGEMENT

In order to manage the complexity of engineering design information, organizations have developed, adapted, and adopted a very wide variety of specific methods and tools so as to have the requisite variety necessary for effectively supporting design. By and large these are point tools; i.e., tools which solve well defined and circumscribed problems, often very effectively. Unfortunately such an agglomeration of point tools further compounds the complexity faced by the engineer since each such point tool requires its own sub-language and other arcana. This suggests that we develop an integrated support environment. However, a sufficiently rich integrated environment, unless carefully designed, could end up being as complicated (if not more so) to the engineer than the original problem. In order to deal with this dilemma we chose to build a support system on a foundation of a few well designed features which, when appropriately composed (in light of the existing information management problem in its context) can generate the desired variety in behavior. The strate-

**Figure 1: Design support system development cycle**




gy, then, is to carefully select features that are both simple to grasp (for the design engineer–the user, and the system designers–the developers) and yet can easily be put together to exhibit a very wide range of behaviors. From a different perspective, and generally because of the attendant complexity, it is almost impossible for any of us as support system builders to know enough of a specific design context to get the larger integrated system right–or even approximately right–the first time.

We are then faced with a fundamental dilemma: either develop good solutions to limited problems (in the sense of limited applicability, domain, or value) or develop comprehensive solutions that tend to be either unusable or just simply wrong. An alternative strategy would be to begin small and gradually build up the integrated system in a series of iterations. Additionally, while integrated environments cannot and will not evolve from point tools, they must be able to incorporate them. Based on our experience and understanding of engineering design, the role of the integrative tool is to provide bridges between the specific to the general, among disciplines, and functions, and to address the collection of information based activities as a whole.

Our approach is created to deal with these observations. We begin by assuming that we will fail in the first few rounds of development. Instead of trying to avoid such failures, we anticipate them, and indeed factor them into the development process in such a way as to rapidly converge to the larger, more reliable, and useful system. This convergence is achieved by the careful construction of basic building blocks which lead to a set of tools, methods, and code modules that exhibit the desired behavior: they are simple to put together, to comprehend, to use, and if necessary to throw away. For example, we have identified a canonical representation for information and knowledge which appears to be extremely general. Thus far, we have been able to represent all types of information and knowledge using this canonical representation.

Hence, while on the surface our iterative approach is not fundamentally different from other approaches in software engineering (Boehm, 1988), the guiding principles, the architecture, the tools and methods, are all internally consistent and designed to support the rapid development of a series of increasingly rich support systems which can then be followed by a hardening phase for final deployment. The basic features of our approach are:

- information flow studies (Finger et al., 1993; Subrahmanian et al., 1993a) which identify the specifics of the situation;
- user participation (Reich et al., 1996a) in as integrated a fashion as possible to engender the maximum possible communication bandwidth as well as legitimacy and buy-in;
- rapid prototyping (Dutoit et al., 1996; Reich et al., 1996b) using specially developed infrastructures and languages designed for the prototype as opposed to class-based development;
- field testing; and
- a distinct code hardening and maintenance step (which might be undertaken by another development group) (Dutoit et al., 1996).

The process we evolved is shown in Figure 1. In light of our experienced observation of design work, the general cycle shown in (a) is reinterpreted as shown in (b). We hasten to add that, in keeping with our general approach of tentativeness, this process is also being continuously refined to suit specific projects and we believe that such refinement will always take place. In order to execute these steps, we have identified five broad methods: (1) information flow-study, (2) user participation, (3) prototyping, (4) testing by users (uncontrolled study) industry/classroom, (5) code maintenance and hardening. The relations between the process steps and the methods is given in Table 2. Each method has to be realized by some infrastructure component or specific tools as shown in Table 3. In this paper, we focus on the development of the infrastructure (columns 2 and 3 of Table 3). The other aspects are discussed elsewhere (e.g., Subrahmanian, 1992; Dutoit, 1996).

## *N*-DIM: AN INFRASTRUCTURE FOR INFORMATION MODELING AND APPLICATIONS

The basic premise of the *n*-dim system is that every member in the product design team operates in an information space, called a *workspace*, that is characterized by the domain of experience and skill of the participant (Levy et al., 1993). The information space of the product is characterized by the union of the information spaces of the individual participants. (This allows us to address the issues associated with multiple locations, languages, areas of expertise, and perspectives of the design participants.)

**Table 2: Objectives/services and methods used to attain them**

| | *1* | *2* | *3* | *4* | *5* |
|---|---|---|---|---|---|
| *Methods*<br><br>*Process Steps* | *Information flow-study* | *User participation* | *Prototyping* | *Testing by users (uncontrolled study) Industry/Classroom* | *Code maintenance and "hardening"* |
| Understanding of the current state of information management | An information map of the Business division studied | Identification of a specific target area for support | | | |
| Development of support systems | | Use and system specification document | A series of working prototypes | Areas of improvement of use and performance before testing | Improving scope. quality, performance, and usability |
| Assessment of support system effectiveness | An information map after system installation | Continuous feedback. | | | |
| Evolution of system | | Continuous identification of new needs | Continuous evolution | Identification of needs (research and improvement) to reduce effort and time | |

This union of information, the product (or organization) information space, is not a straightforward union as there are terminological inconsistencies across the information spaces and well understood and not so well understood relations between the elements of the information space. Further, in each information space of the participants and in the product information space, the organization of information itself evolves as process and product understanding increase to form a shared memory (Konda et al., 1992). The objective is to support the individual evolution of knowledge and the collective evolution of knowledge in the form of information structures that are constructed by the participants in the course of the product development process. The history of both process and product is critical to ensuring that evolution takes place in an effective manner. This is important both to the short term evolution of a project and to a long term evolution of policies of operation. To address this, we have taken as our hypothesis that a generalized graph modeling environment that operates over the elements (other information structures–graphs and atomic information elements) in the information spaces is necessary to capture the structure and evolution of information and knowledge, both formal and informal and individual and group. We hypothesize that this generalized graph is a canonical representation from which all others can be derived.

## Concepts in *n*-dim

*Information Objects*: Information objects are of two types: atomic objects and structured objects. Atomic objects are strings, numbers, images, audio fragments, etc. They are not decomposable. Structured objects are graphs whose nodes are atomic objects or other structured objects. The graph includes named links that can exist between any two nodes.

*Models:* For convenience we use the term model to denote both atomic and structured objects. Objects are referenced in a model rather than being embedded in a model. Models imply object association by having their pointers collected together. Named links are used to describe the relationships between the object pointers.

*Flat space:* Flat space is a term we have given to the conceptualization of an information space where any model is directly referable. This allows for the creation of a user defined set of relationships across information objects of any granularity. Users have the ability to create any arbitrary model over a subset of the entire collection of information objects in the information space.

## Modeling languages

A model can be abstracted to create a set of building blocks that correspond to the type of information objects in the graph and the types of named links in the graph. These abstractions can be made to create a vocabulary which can, in turn, be used to create other model instances. For example, one can create an object and abstract the features of that object in creating another object of different dimensions, scale, etc. Here, one has developed a language for describing that particular artifact. Languages restrict the type of objects and named links users may use to construct further instances of the model type. Modeling languages are

**Table 3: Methods, Tools, and Outcomes**

| | *1* | *2* | *3* | *4* |
|---|---|---|---|---|
| *Tools*<br><br>*Methods* | *Questionnaire and interviews* | *Infrastructure for evolving information systems* | *Layered modular architecture* | *Social Science methods (regression/multiple regression/ natural language analysis)* |
| Information flow-study | Identifying communication gaps | | | |
| User participation | | | | Source of action research methodology |
| Prototyping | | Support for quick prototyping, customization, legacy tool integration and evolving the infrastructure | Potential re-use of existing legacy layers (e.g., DB) | |
| Testing by users (not controlled study) Industry/ Classroom | | High usability to support early testing | | Identification of needs (research and improvement.) to reduce effort and time |
| Code maintenance and "hardening" | | Support for improving performance of validated code | Supports improving layers with new technologies | |
| Basic research (e.g., study the role of Communication in design projects) | | | | Identification of needs (research and improvement.) to reduce effort and time |

models; therefore, any model can be used to define the grammar of other models.

Such a grammar defines what is a correct instance of a model (its semantics) in a modeling language. Additionally, we can increase the power of this approach by attaching behavior to a model using what we call operations. In essence, operations are pieces of code which, when executed with the relevant parameters, allow a model to automatically perform actions on behalf of the user (or the modeling language designer). For example, an operation on a model might be used to inform the user when someone adds a part to that model. Symmetric to the semantics behavior outlined above, operations are inherited by model instances created by using the model to which those operations are attached as the modeling language. Thus, the system allows for standardization of modeling languages and their use and for the evolution of new graph types from the model instances. As a result, the system supports both deductive and inductive approaches to the modeling process.

As more modeling languages and operations are developed, they start to form repositories whose items can be reused for creating new languages or applications or adapting old ones. We have built the infrastructure so that it will support the flexible creation of such repositories and their effective reuse.

## Evolution: Private, Public, and Published

History is critical to effective evolution and ordered evolution is essential to recording history. We have developed an ordered evolution of the system with the following three facilities. These facilities deal with different levels of granularity: private, public, and published.

*Private:* Private, as the name denotes, is the private information space of the individual. There are no restrictions on how a private space is managed. The users can add, delete, and restructure their information objects.

*Public:* This mode of operation is a public forum area. Here the primary objective is to provide the ability to all participants to share and add to the model, both synchronously and asynchronously. As with any forum, the language of the forum is restricted to the purpose and domain of discourse as determined by the participants or the existing body of knowledge. History can be recovered by viewing a model's state in time.

*Published*: The published mode of operation is an archival facility. Any information object that is entered into the published information space cannot be withdrawn (i.e., it is persistent). Changes are published by copying, modifying and then re-publishing a model. The system automatically records the act of

copying and re-publishing, thereby keeping a branched (time and owner) history of the model. The model that allows for the tracing of the origin of the document is itself a graph within the system.

In addition to the need to record history, the need to search for information and effectively visualize information in different ways is equally important. As more information is created in *n*-dim, knowledge could be organized in repositories that ease the location and reuse of relevant knowledge.

The above characterization of the system is necessarily abstract, as the details of the system cannot be described in this limited space.

### Strength and weaknesses of *n*-dim

The primary strength of the system is its approach to dealing with software development and knowledge development in an evolutionary manner. The system combines evolution, history, and modeling within the same framework–the framework of graph based modeling. The other main strength of the system is its flexibility in allowing the easy integration of legacy tools, they can be invoked from within the system in their native form or can be integrated fully into the system. Further, the system also allows for the creation of new tools by the user as needed (Dutoit et al., 1996). For example, we are integrating a Natural Language Processing (NLP) tool to allow us to handle terminological differences in design contexts. We are also expanding our research efforts in creating a graphically based end-user scripting language capability to make the above tasks easier.

Another strength of our system is the infrastructure upon which it is built. The flexibility of the object tool kit allows for extensions to the system incrementally without damaging the underlying system (Dutoit et al., 1996). This problem is acute in many commercial systems, where moving from one version to another version often requires a transition time which may last from hours to weeks.

The *n*-dim system itself is an infrastructure that is customized to particular applications and within which new applications can be built. For example, we have developed several types of issue-based discussion applications and tested them (e.g., IWEB, Coyne et al., 1994). *n*-dim is not a system that can just be bought and installed. This can be viewed as a weakness from a commercial point of view and we are keeping that much in mind as we plan for commercialization. But a flexible infrastructure with the strong capabilities of *n*-dim including its quick prototyping and code hardening capabilities is potentially a great strength for any organization that chooses to make the investment.

## HOW *N*-DIM ADDRESSES A VARIETY OF INFORMATION ACTIVITIES

We have developed the *n*-dim infrastructure based on a small set of features we have identified in addition to the graph-based canonical representation of information described in the previous section. We have also developed some applications using the infrastructure. In order to ensure that the goal of the information infrastructure conforms to the needs of the design context, we have developed a table of influences (Table 4) to provide an understanding of how features and applications in the *n*-dim system are developed with reference to their impact on the dimensions of complexity of design contexts. As contexts are studied and applications are developed, a cycle of hypothesizing and evaluating the impact of the applications on the dimensions of the design context occurs. This cycle enables us to perform a continual refinement of the core set of features that constitute the integrative environment.

We have created Table 5 for information management activities and their support with respect to *n*-dim features and applications. The purpose of the table is to provide a check list to ensure that the scope of the evaluation of the impact of features and applications covers individual information management activities. As mentioned earlier, the development of an information system requires the search for a minimal set of features and applications that will allow for the matching of the needs and requisite variety demanded by the context. Thus, it is important that we use a check list of factors such as the dimensions of the design and the dimensions of the information management activities in understanding the implications of any feature and application added to the system.

Tables 4 and 5 illustrate the endeavor of designing information management systems as a design problem where the impact of several interacting factors are unknown in specifying the correct design. They serve as drivers for creating and testing hypotheses about the utility of particular features and applications in an integrative environment. By using this iterative and evolutionary approach we believe an integrated information management for design can be created to match the complexity and variety exhibited by a design context.

To illustrate this process, consider the example of NLP tools in *n*-dim. We made the hypothesis that variations in the terminology used by designers could be exploited to understand the design process better. For instance, designers using a large number of terms at the onset of integration could indicate that numerous concepts are being discovered and reconciled. This high rate of discovery so late in the process could be caused by the failure of designers to communicate effectively before the integration phase.

**Table 4: *n*-dim features addressing design context dimensions**

| *Features and Applications of n-dim* / *Dimensions of design context* | *General Graph* | *Flat Space* | *Modeling Languages* | *Publication* | *Tool Encapsulation* | *Workspaces* | *Scripting Language* | *Search* | *Repositories* | *Issue-Based Discussion* | *NLP Tools* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | | | | + | | | | + | | + | |
| Place | | | | + | | | | + | | + | |
| Culture | + | | + | | | + | | | | | + |
| Languages | + | + | + | | | + | + | | | | + |
| Tools | | | + | | + | | + | | + | | |
| Expertise | + | | + | | + | | | | | + | + |
| Perspectives | + | + | + | | | + | | | | + | + |
| Interaction | | | | | + | | + | | + | + | |
| Usability | + | | + | | + | | + | | + | | |

**Table 5: *n*-dim features addressing IMA**

| *Information Manipulation* | *Knowledge Building* | *Collaboration* | *Features and Applications of n-dim* / *Information Management Activities* | *General Graph* | *Flat Space* | *Modeling Languages* | *Publication* | *Tool Encapsulation* | *Workspaces* | *Scripting Language* | *Search* | *Repositories* | *Issue Based Discussion* | *NLP Tools* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| + | | | Creating Information | + | + | + | | | + | | | + | | + |
| + | + | | Structuring Information | + | + | + | | | + | | | + | | + |
| + | | | Finding Information | | | | | | | | + | + | | + |
| | + | + | Sharing information | | | | + | | | | + | + | + | |
| + | | | Information Visualization | | | + | | + | | | + | | | |
| + | | + | Using Standards | + | | | | + | | + | | | | |
| + | | + | Sharing Tools | | | | | + | | + | | + | | |
| + | | | Integrating Legacy Tools | | | | | + | | + | | | | |
| | + | + | Capturing History | | | + | + | | | | | + | | |
| | + | + | Capturing Rationale | | | + | + | | | | | + | | |
| | + | | Learning by Induction | + | + | + | | + | | | + | + | | |

To test this hypothesis, we studied a number of software projects that relied on electronic means of communication (e.g., electronic mail, newsgroups) (Bruegge and Dutoit 1997; Dutoit, 1996). We used NLP tools to extract noun phrases from the electronic messages and developed a statistical model to analyze the factors that influenced their variations[2]. It was found, for example, that delayed negotiation of terms between design teams was indicative of future problems at the integration phase. More generally, we found that communication metrics can be used as indicators of problem areas and potential downstream risks to the design project. Based on this study, we are currently deriving a basic set of analysis and diagnostic tools that can become part of the support environment and, if desired, used by designers to forewarn them. It is from this experience that the "+" sign of the NLP negotiation cell in Table 5 was obtained.

As we learn more from the empirical study of design, the contents of these tables will evolve. Entire rows (or columns) may be consolidated, deleted, or created as technologies, work processes, knowledge, and organizational culture change. On a smaller scale, as our knowledge grows, the entries in each cell could change (from a "+" to a blank or vice versa). Perhaps of greater value, the tables can be used as guides in selecting specific studies or implementations as indicated by blank cells, rows, or columns.

## SUMMARY

In this paper, we have outlined an approach to creating design support systems that is based on observations of design practice. The approach is an iterative process composed of data-driven hypothesizing and creating, testing, and evaluating support systems in the design context to understand the impacts they have on information management activities. In developing our methods, we work with an organization as partners to build and maintain support systems for knowledge capture, dissemination, and maintenance within the firm. In these partnerships the client provides the context, methods, and tools for doing design, we provide our tools and methods for developing support systems, and as a joint team we develop the system. This team develops a prototype support system with the user and tests the system for effectiveness. If during development we find there are needs that cannot be fulfilled by current technologies or we need methods to understand information flow dynamics in a group, then we look for them in other disciplines or develop them as part of our basic research. The desired outcome is that we walk away with a deeper understanding of group design and management of knowledge in organizations and that our partner has a system for knowledge capture, dissemination, and maintenance that improves their design performance.

2. This is an example of the use of social science approaches shown in Table 3.

## ACKNOWLEDGMENTS

This work has been supported by the Engineering Design Research Center, an NSF Engineering Research Center.Support has also been provided in part by Asea Brown Boveri Ltd. and Union Switch and Signal, Inc.

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# Categorical Foundations for System Engineering

**Chapter** · January 2018

DOI: 10.1007/978-3-319-62217-0_32



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*15th Annual Conference on Systems Engineering Research*
*Disciplinary Convergence: Implications for Systems Engineering Research*

*Eds.: Azad M. Madni, Barry Boehm*
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# Categorical foundations for system engineering

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***Abstract***

***In this paper we argue that category theory (CT), the mathematical theory of abstract processes, could provide a concrete formal foundation for the study and practice of systems engineering. To provide some evidence for this claim, we trace the classic V-model of systems engineering, stopping along the way to (a) introduce elements of CT and (b) show how these might apply in a variety of systems engineering contexts.***

***Keywords: Category theory, Foundations of system engineering, Mathematical modeling***

## Introduction

Systems are becoming more complex, both larger and more interconnected. As computation and communication in system components goes from novelty to the norm, this only becomes more true. In particular, we have no generally accepted method for designing, testing and analyzing systems which mix both physical and computational dynamics. We believe that a new formal foundation is required to model and study such complex systems.

Existing approaches, typified by the V-model of systems engineering, are more heuristic than formal. First we conceptualize the system, setting our various requirements and assumptions. Next we refine this into a functional decomposition which details how our system will meet its goals. In realization, we map these functions to components of our systems. Finally, we integrate these components into a true system, testing along the way, before releasing the system for operation.

This says what we need to do, but not how to do it. A formal foundation would supplement this framework with concrete tools and formal methods for accomplishing each step. Our goal in this paper is to propose a candidate approach for such a foundation, based on a branch of mathematics called category theory (CT).

We should mention some prior work associating CT and systems engineering. For example, CT is listed as a foundational approach in the Systems Engineering Body of Knowledge (SEBOK, [1]), although there is little detail associated with the entry. More substantively, Arbib & Manes [2] studied applications of CT in systems control in the 1970's. This work was largely stymied by the unfamiliarity of categorical ideas and the lack of good tools for implementing them (on which we will have more to say in the conclusion).

CT is the mathematical theory of abstract processes, and as such it encompasses both physics and computation. This alone makes it a good candidate for foundational work on modern systems. As we proceed, we will also argue for other virtues including expressivity, precision, universality and modularity among others.

To make our argument, we will trace through the classic V-model of systems engineering,

demonstrating along the way how CT might apply at each step in the process. We have chosen the V-model not for validity (it oversimplifies) but merely for familiarity.

In tracing the V, we hope to accomplish two things. First, we aim to demonstrate the range of categorical methods in order to demonstrate that CT might provide a holistic foundation for systems engineering. Second, and more important, we hope to introduce systems engineers to the language and methods of CT, and pique the interest of the systems engineering community to investigate further. Our hope is that one day soon this paper might serve as the preface to a much deeper study that systems engineers and category theorists might write together.

## 1. Conceptualization

The first role for CT in systems engineering is as a precise technical language in which to express and analyze models of systems information, ranging from theoretical predictions to raw data. The key feature of CT in this respect is its abstraction. We can form categorical models from graphs, from logical ontologies, from dynamical systems and more, and we can use categorical language to analyze the relationships and interactions between these. To get a sense of what this looks like, we will model some simple system architectures and the relationships between them.

The categorical model for an abstract network is remarkably simple:

$$\mathcal{N} = \left\{ \texttt{Channel} \underset{\texttt{target}}{\overset{\texttt{source}}{\rightrightarrows}} \texttt{Node} \right\} \tag{1}$$

The first thing to observe is that a category contains two types of entities, called *objects* and *arrows*. Intuitively, we think of these as sets and functions, though they are abstract in the model itself. An *instance* of the model replaces abstract objects and arrows with concrete sets and functions. It is not hard to see that any network can be encoded as an instance of $\mathcal{N}$, as in figure 1.

The key difference between categories and directed graphs are the construction principles which allow us to combine the elements of our models. Foremost among these construction principles is arrow *composition*; whenever we are given sequential arrows $A \xrightarrow{f} B \xrightarrow{g} C$, we can build a new arrow $f.g: A \to C$. Another way to think of this is, when we draw categories as directed graphs, the arrows include *paths* of edges as well as individual arcs. We also allow paths of length 0, called *identities*.

To see why this is useful, consider the following simple model for a hierarchy of depth $\leq n$:

$$\mathcal{H} = \left\{ 1 \xrightarrow{\texttt{root}} \texttt{Node} \circlearrowleft \texttt{parent} \;\middle|\; \texttt{parent}^n = \texttt{const.root} \right\} \tag{2}$$

Here the primary structure is the self-arrow `parent:Node→Node`, which sends each node to the level above it in the hierarchy. By composing `parent` with itself we can trace our way up the hierarchy from any node.

By itself, this is too flexible. There is nothing to ensure that all nodes are part of the *same* hierarchy and, even worse, our ``hierarchy'' might contain loops! We can eliminate these worries by demanding that the `parent` map is ``eventually constant'': after $n$ repetitions, every node ends up at the same place. This

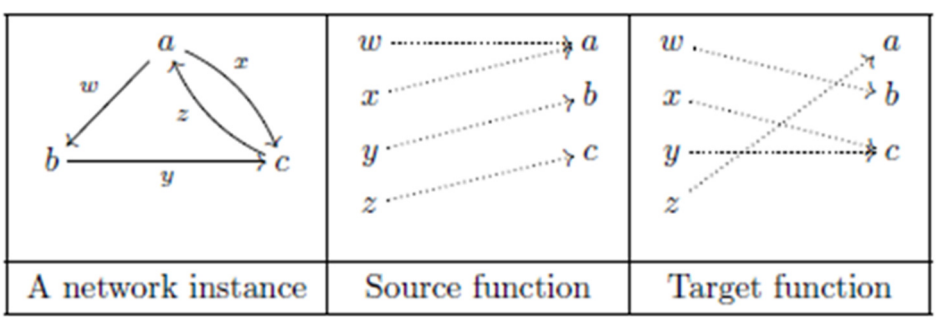



Fig. 1: Network as an $\mathcal{N}$-instance

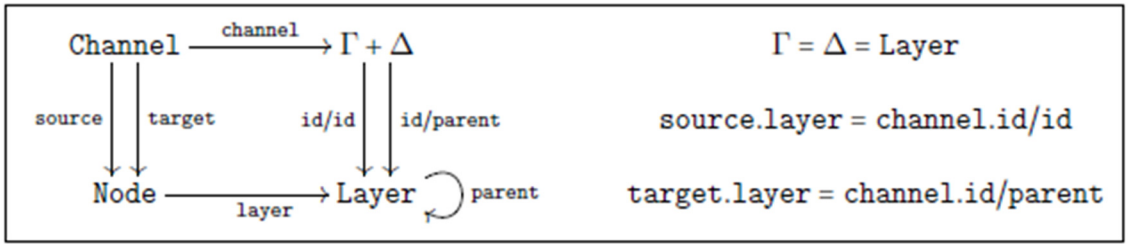



Fig. 2: Categorical model for layered architectures

involves two ingredients: a *construction* and a *path equation*.

Categorical constructions generalize most set theoretic operations such as unions, intersections and Cartesian products. The terminal object 1 stands in for a singleton set, and allows us to express the notion of a constant value `root`∈`Node`. The path equation $\texttt{parent}^n = \texttt{const.root}$ forces the $n$th parent of any node to equal `root`, ensuring a single hierarchy with no loops.

A more interesting example is the layered architecture $\mathcal{L}$ (figure 2), in which channels must conform to a hierarchy of layers. Here the path equations constrain where channels may occur, while the + and / constructions express the fact that channels may form either between layers (Γ) or within a layer (Δ).

All of these models are fairly trivial. The main point is that the sorts of class modeling which systems engineers already do is not too far away from a precise formal language. By carefully modeling our concepts at the early stages of systems engineering we can express requirements more precisely, identify misconceptions and inconsistencies, and establish concrete domain-specific languages. Best of all, we get both intuitive graphical presentations like those found in UML/SysML class diagrams without sacrificing the semantic precision associated with OWL and other formal approaches to ontology.

CT also goes beyond these existing languages. A *functor* is a mapping between categories; it sends object to objects and arrows to (paths of) arrows, without changing the effects of composition. These maps, along with other constructions like colimits and natural transformations, allows us to explicitly identify and represent the relationships between individual categorical models, thereby linking them into larger networks. This allows semantic ontologies to emerge organically from the bottom-up, grounded in practice, in contrast to ``upper ontology'' approach (e.g., the Basic Formal Ontology [3]), which tries to impose semantic structure from the top down.

A simple example is the idea that a hierarchy is a special type of network. This fact can be formalized as a functor $H{:}\mathcal{N}\to\mathcal{H}$. To define $H$ we ask, for each component of $\mathcal{N}$, what plays an analogous role in $\mathcal{H}$? The translation for `Node` is clear. In the hierarchy we have one channel for each node, so `Channel` also maps to the same object `Node`. Since each channel maps from a node to its parent, `target` corresponds with `parent` and `source` with the identity (zero-length path). Putting it all together, we have the functor depicted in figure 3(a). Similarly, we can identify one hierarchy (of layers $\mathcal{L}$) and two networks (of channels $\mathcal{C}$ and layers $\mathcal{L}'$) in the layer architecture, corresponding to the four functors in figure 3(b). We

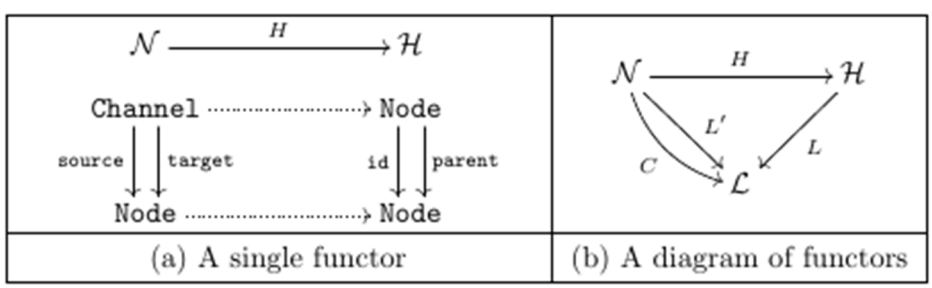



Fig. 3: Functors translate between categorical models

even have a path equations--$H.L = L'$--which acknowledges that the network of layers in $\mathcal{L}$ is just the same as the network in $\mathcal{H}$ which is constructed from the hierarchy in $\mathcal{L}$.

The stylized models and relationships presented here are fairly trivial, but the general method of categorical modeling is quite powerful. By varying the constructions we allow ourselves to use, CT modeling can range in expressiveness from simple equations to full higher-order logic [12]. For more thorough introductions to categorical modeling, see [23] or [10]. The main thing to remember is that categorical methods provide tools for expressing *and relating* our formal models.

## 2. Decomposition

In the last section we met all the essential elements of category theory--objects and arrows, composition, identities--except one: the associativity axiom. Given a sequence of three composable arrows $A \xrightarrow{f} B \xrightarrow{g} C \xrightarrow{h} D$, we could first compose at $B$ and then at $C$, or vice versa. Both should yield the same result: $(f.g).h = f.(g.h)$. When applied to processes, this axiom is so obvious it is difficult to express in English:

Doing $f$ and then $g$, and then doing $h$
is the same as
doing $f$, and then doing $g$ and then $h$.

Because of this, there is no need to keep track of parentheses when we compose arrows.

This allows us to describe complex processes based on only two pieces of information: (i) the descriptions of simpler subprocesses and (ii) the way they were chained together. Of course, systems engineers know that complex emergent phenomena may arise from simple subprocesses. This does *not* mean that compositional, categorical mathematics does not apply. Instead, it means that the compositional representations of such systems may require greater complexity than the naïve models we might produce from scratch. By demanding compositionality from the outset, we are forced to build interaction into our models from the ground up!

One important step in this direction is to generalize the sorts of composition that we allow. In fact, there are *many* different flavors of category theory, each of which supports a different notion of composition. The plain categories that we met in the last section allow only unary (single-input) processes and serial composition. Some varieties like groups, which formalize the mathematics of symmetry, restrict ordinary categories to obtain simpler structures. Others like process categories and operads add in additional construction principles like parallel composition and multiple input/output. Through these constructions, categories axiomatize the most fundamental concepts in systems engineering: resources and processes [7].

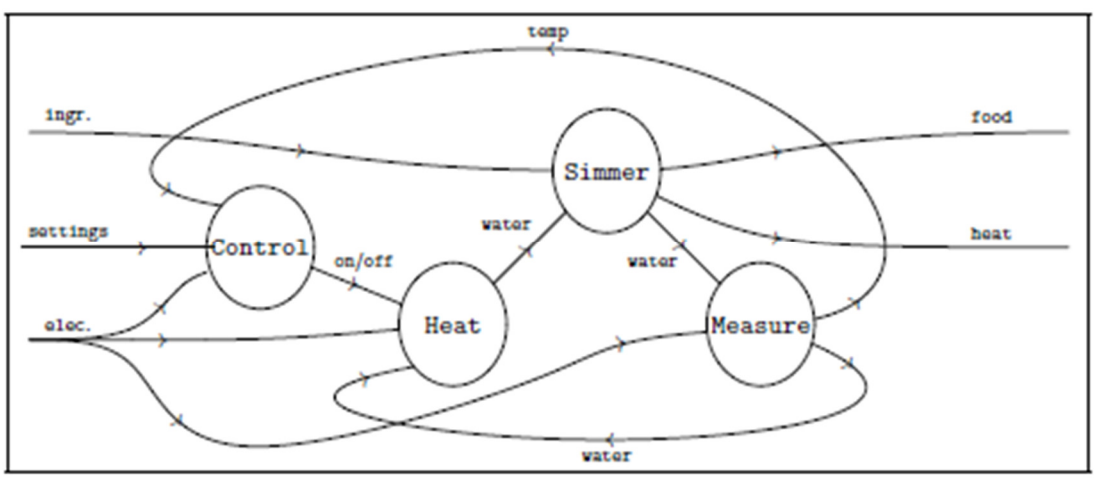



Fig. 4: Process decomposition as a string diagram

All of these share a common theme of composition and associativity. For groups, this allows us to describe the way that arbitrary rigid motions can be decomposed into translations and rotations. More generally, this allows us to express complicated structures in terms of smaller and simpler pieces. It can also help to show when a chain of complicated operations has a simple and predictable outcome.

*Process categories*, which are embody the mathematical structure of multi-resource functional decomposition [7,4]. In the mathematical literature these are often refered to as "traced symmetric monoidal categories", but we feel that this nomenclature is too imposing given their simplicity and importance. One particularly nice feature of these structures is that process categories support a graphical syntax called *string diagrams* like the one in figure 4. Completely formal and technically precise, these diagrams are nevertheless as intuitive and easy-to-read as flow charts.

Where string diagrams represent process flows, another class of structures called *operads* formalizes the notion of a parts decomposition [21]. In an operad, the objects are interfaces and the arrows are "wiring diagrams" which connect a set of small interfaces into one larger component. Here associativity says that there is only one meaning for the phrase "a system of systems of systems."

These representations make it easier to talk about relationships across scale. Some or all of the subprocesses in the figure 4 will have their own process decompositions. The only substantive constraint on these decompositions is that they have the appropriate input and output strings. This leaves us with one high-level categorical model $\mathcal{P}$ for the entire process and several low-level models $\mathcal{Q}_i$ for the individual subprocesses.

To express the relationship between these, we first combine the low-level pieces into a single aggregate model $\mathcal{Q} = \oplus_i \mathcal{Q}_i$. This involves an operation called a *colimit* which generalizes set-theoretic unions; building them requires explicitly representing the overlap between different models. Once we build the aggregate model, we can then define a functor $\mathcal{P} \to \mathcal{Q}$ which essentially pastes copies of the smaller diagrams $\mathcal{Q}_i$ into the appropriate bubbles from $\mathcal{P}$. This identifies an explicit model for the total high-level process $\mathcal{P}$ inside the aggregate low-level model $\mathcal{Q}$. Furthermore, we can also allow multiple decompositions for a given subprocess, providing a framework for modularity and versioning.

## 3. Realization

During realization we turn our abstract models into concrete realizations. In spirit, the relationship between these two is analogous to the that between the logician's notions of syntax and semantics. Roughly speaking, syntax is what we say and semantics is what we mean, or what we are talking about. Models are like syntax: they describe how a product or system is supposed to work in terms of both structure (decomposition and component interaction) and behavior (requirement and verification specifications). Attaching semantics to these models means assigning each syntactic component to some sort of concrete entity, in a way that mirrors the structure and behavior of the model.

Ultimately these concrete entities will be physical components and functioning source code, but before we reach that point we must pass through many other, more abstract semantics. These might range from the formal verification of a critical algorithm to a stochastic model of user behavior, but most have some flavor of simulation. The motivating example to keep in mind is the simulation of a system in terms of (discrete, continuous or hybrid) dynamical systems [15].

The key feature of the logician's semantics is compositionality: if we want to determine the truth of a complex logical formula, it is enough to look at the truth values of its subformulas. This might seem to fail for a given dynamical system: just because each component of my system is safe in isolation hardly guarantees safety of the composite system. Doesn't the existence of emergent phenomena mean that the behavior of a complex system is *not* determined by the behavior of its components? This misunderstanding rests on a conflation of two distinct notions of "behavior".

We can think of system behavior as a path through some high-dimensional state space; component behavior is the projection of this path onto the subspace of component parameters. The problem is that component dynamics in isolation trace out different paths than the projected system dynamics would. This is why component safety in isolation does not entail system safety, even for the same component metrics. This also means that there is no hope of composing individual component behaviors to derive system behavior.

However dynamical models, the differential equations which generate these paths, *are* composable: we can derive the dynamical equations of a system from the dynamics of its components [24]. The formula for this derivation will, of course, depend on how the components are connected to one another. Each diagram like the one in Figure 4 generates its own formula. CT structures this relationship, making the requirements of compositionality explicit through the language of categories and functors.

Logical semantics involves three main elements: (i) a syntactic model to be interpreted, (ii) an assignment of syntactic elements to semantic objects, and (iii) a satisfaction relation which determines whether this assignment meets the requirements of the model. However, traditional logic operates in a fixed context of sets and functions (deterministic semantics), while CT broadens this to allow stochastic semantics, dynamical semantics and more. Thus categorical semantics adds one further element, (iv) a universe of semantic entities.

This approach relies on an important though informal distinction in CT between smaller, ``syntactic'' categories and larger, ``semantic'' categories. Syntactic categories are like the architectural models described from section 1, built directly from graphs (generators), path equations (relations) and categorical structure (constructions).

Semantic categories instead use some other formalism, like set theory or matrix algebra, to define the objects and arrows of a category directly. The prototypical example is the category of sets and functions, denoted **Sets**, where composition (and hence path equations) is computed explicitly in terms of the rule $f.g(x) = g(f(x))$. Many other semantic categories like **Graph** (graphs and homomorphisms) and **Vect** (vector spaces and linear maps) can be constructed from set theoretic entities.

Once we adopt this viewpoint, the relationship between syntax and semantics can be represented as a functor from one type of category to the other. We have already seen one example of this approach, in figure 1, where we described a network instance in terms of a pair of functions. This is exactly the same as a functor $I{:}\mathcal{N} \to \mathbf{Sets}$: we map objects of $\mathcal{N}$ to objects of **Sets** and arrows of $\mathcal{N}$ to arrows of **Sets** (i.e., to sets and functions).

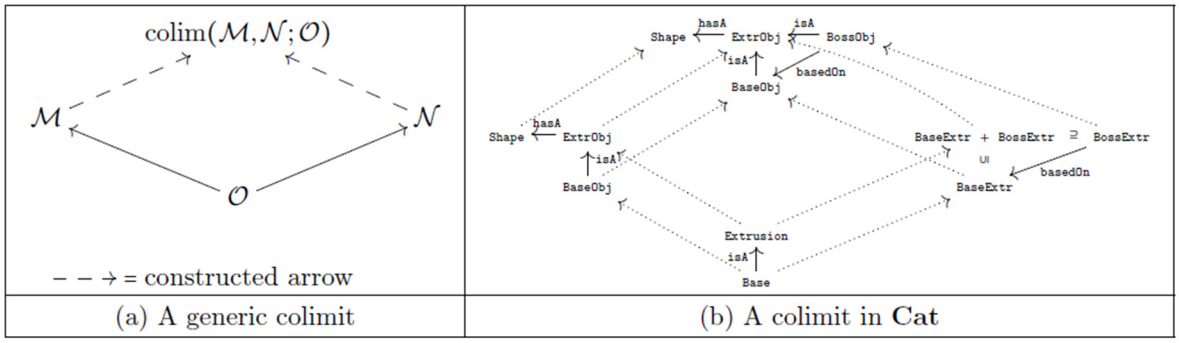
The satisfaction relation for the semantic interpretation is determined by the preservation of categorical structure. A good example is the coproduct "+", used in our model for the layered architecture $\mathcal{L}$ (figure 3). Not all functors $\mathcal{L} \to \mathbf{Sets}$ are semantically valid, only those which map the abstract coproduct $\Gamma + \Delta \in \mathcal{L}$ to a concrete coproduct (disjoint union) in **Sets**. We say that a model of $\mathcal{L}$ should preserve coproducts. Implicit in any categorical model is a minimal set of construction principles required to preserve full semantics.

Once we recognize that the traditional (logical) interpretations for a model $\mathcal{M}$ are the structure-preserving functors $\mathcal{M} \to \mathbf{Sets}$, we are in an easy position to generalize to a much wider array of semantics. We have explicitly identified the necessary structural context (e.g., coproducts) $\mathcal{M}$, so we can replace **Sets** by any other category which has these same features. We can use a category **Dyn** whose objects are dynamical systems; a functor $\mathcal{M} \to \mathbf{Dyn}$ provides dynamical semantics. There is a category **Prob** whose arrows are probabilistic mappings; a functor $\mathcal{M} \to \mathbf{Prob}$ describes stochastic semantics for $\mathcal{M}$. There is a computational category **Type** where arrows are algorithms; functors $\mathcal{M} \to \mathbf{Type}$ provide computational interpretations for $\mathcal{M}$. We can often compose these, for example mapping a model to a dynamical system, and then mapping this to a computational simulation. Sometimes we can even mix semantics together, so that in figure 4 we could give dynamical models for `Heat` and `Simmer`, a computational model of `Control` and a stochastic `Measure`, and compose these to give a hybrid dynamical model for the whole system.

## 4. Integration

The main role of our models in system integration is to collect and manage the tremendous amount of structured data collected and analyzed during the integration process. This data is necessarily heterogeneous, multi-scale and dispersed across many models and experts. Categorical models have several nice features which can support the federation of this data.

First of all, we can regard a finite syntactic category $\mathcal{M}$ (like one of the architectural models in section




(a) A generic colimit | (b) A colimit in **Cat**

Fig. 5: The colimit construction

1) as a database schema [14,19,20]. Roughly speaking, the objects are tables and the arrows are foreign keys. This means that we can use the models already produced during conceptualization and decomposition to store the data generated during integration. Formally this depends on the functorial semantics discussed in the previous section; we can think of an instance of the database as a functor $I{:}\mathcal{M} \to \mathbf{Sets}$ mapping each table to a set of rows. Notice that this approach automatically ties the data that we produce to our semantic models.

A more significant challenge is the dispersion of data across many engineers using many different models. In order to build a holistic picture of our system, we need some way of putting models together and aggregating the data they contain. The CT approach involves a categorical construction called a *colimit*, together with an additional twist.

A colimit is a categorical construction that generalizes unions, allowing us to build new objects by gluing together old ones. For example, any graph can be constructed using colimits by gluing edges together at nodes. To integrate two objects using a colimit, we first explicitly identify their overlap as a third object, along with two maps embedding the overlap into each component. Given this data, the colimit construction then produces a fourth object together with two maps which embed the original components into the new object. See figure 5(a).

The twist is that, instead of looking at categorical constructions inside our models, now we are interested in performing colimits *with* our models. This approach depends on the fact that CT is self-referential: the methods of CT can be applied to study categories themselves. In particular, there is a semantic category **Cat** whose objects are categories and whose arrows are functors. Colimits in this and related semantic contexts can be used to define model integration. A very simple example is given in figure 5(b).

In fact, we can form colimits from any number of components, so long as we accurately represent their overlaps (and overlaps of overlaps, etc.), providing a scheme for wider integrations. However, representing all those overlaps may be inefficient. Another alternative is to integrate serially, adding in one new model at a time. CT provides us with a language to state and prove that either approach is valid, and that the two options will yield equivalent results [25].

As for heterogeneity, CT constructions called *sheaves* have recently been proposed as ``the canonical datastructure for sensor integration'' [18]. The main idea is that when different of sensors capture overlapping information, it must be restricted or transformed before it can be compared. In the simplest example, to identify overlapping images we must first crop to their common ground (restriction) before comparing the results. A simplistic algorithm would ask for perfect agreement on the restriction, but a more sophisticated integration might allow small differences in shading or perspective (transformation). We can also compare different types of information, so long as we can project them to a common context; we might match up audio and video by translating both to time series and looking for common patterns. CT provides the language and spells out the requirements for translating between contexts in this way.

Finally, by mixing colimits with functors, we can connect our models across layers of abstraction [6]. Suppose that $\mathcal{H}$ is a model one level of abstraction above that of $\mathcal{M}$ and $\mathcal{N}$ in figure 5. Both $\mathcal{M}$ and $\mathcal{N}$ are

more detailed than $\mathcal{H}$, but each only covers half the range. When we put them together, though, they *do* cover the same range: every entity of $\mathcal{H}$ can be defined by mixing structures from $\mathcal{M}$ and from $\mathcal{N}$. Formally, this means that we can construct a refinement functor $\mathcal{H} \to \mathrm{colim}(\mathcal{M},\mathcal{N};\mathcal{O})$ which tells us how to compute high-level characteristics in terms of low-level ones, helping to trace high-level requirements to low-level performance.

**5. Operation**

In operation, systems are never static. Components fail and need to be replaced. New models and versions require tweaks to existing production and control system. New technology or regulation changes the environment in which our systems operate. Because of this, it is critical that our models should be relatively easy to maintain and update. Here again, categorical methods have some nice features which recommend them.

One significant challenge in updating a model is that we must take existing data attached to the original model and shift it over to the new one. Thinking of our models as domain-specific languages, we must translate our data from one language to another. These processes are often messy and ad hoc, but categorical constructions can help to structure them.

As we mentioned in the last section, a class-type categorical model $\mathcal{N}$ like those discussed in section 1 can be translated more-or-less directly into database schemas [14,19,20] where objects are tables and arrows are foreign keys. An instance of the database is a functor $\mathcal{N} \to \mathbf{Sets}$ which sends each abstract table to a concrete set of rows. By generating our data stores directly from models, our data is automatically tied to its semantics.

We can then use functors to formalize the relationship between old and new models. This will provide a dictionary to guide our translation. Moreover, expressing the transformations in these terms can help to organize and explain certain inevitable features of this process.

A good example is the phenomenon of duality between models and data. A meticulous reader will have noted that, in the discussion of architectural models, we said that “every hierarchy is a special kind of network”, but then proceded to define a functor $\mathcal{N} \to \mathcal{H}$. The direction has reversed!

The categorical formulation explains this fact: given a functor $\mathcal{N} \to \mathcal{H}$ and an instance $\mathcal{H} \to \mathbf{Sets}$, we can compose these at $\mathcal{H}$ to obtain an instance $\mathcal{N} \to \mathbf{Sets}$. So every functor between syntactic models defines a mapping of instances *in the opposite direction*. We might call this operation model restriction or projection, and categorically speaking it is simply composition.

While composition allows us to restrict data backwards along a functor, subtler and more significant constructions called *Kan extensions* allow us to push data in the same direction as a functor [20]. In many cases, data demanded by the new model will be unavailable in the old; in others, we may split one concept into two, or vice versa. In all of these cases, Kan extensions provide explicit instructions for building a “best approximation” to the old data, subordinate to the new schema.

Remarkably, the same operation of Kan extension can also be used to encode quantification in formal logic [17] and periodic states in dynamical systems [15]. This points to a critically important aspect of categorical methods: uniformity. The abstraction of CT allows us to apply the same set of tools to a remarkably diverse set of problems and circumstances.

This can be problematic for beginners: even simple applications of CT may require learning several abstract constructions. Why bother, when there are easier solutions to this problem or that? The value of the CT approach only becomes apparent for more substantive problems, where the same familiar tools can still be applied.

Another nice property of categorical models is modularity, which is supported by the fact that the colimit construction is a functor. Suppose, for example, that we extend one of the models in figure 5(a) via a functor $\mathcal{N} \to \mathcal{N}'$. A categorical construction principle for the colimit then guarantees that we can build a new map $\mathrm{colim}(\mathcal{M},\mathcal{N};\mathcal{O}) \to \mathrm{colim}(\mathcal{M},\mathcal{N}';\mathcal{O})$. This allows us to update domain-specific models locally and then lift these changes to a global context.

More generally, the category theoretic property of naturality (over the diagram of the colimit) encodes the restrictions which must be satisfied if updates to multiple components are to be consistent with one another. Other categorical constructions called *fibrations* have been useful in formalizing more general

bidirectional transformations, where updates may not be consistent with one another [13,9]. In fact, the elucidation of this concept of naturality was the motivating goal in the original development of CT; categories and functors were merely the supporting concepts which underpin ``natural transformations'' [11].

Our discussion here has tried to indicate the potential breadth of categorical analysis. In so doing, we have sacrificed depth in return. There is much more to be said.

## Conclusion

One by one, the elements of category theory may not seem so impressive. We already have OWL for representic semantic information, and good tools for interacting with databases. The UML/SysML language family allows us to build graphical models and translate them into code stubs for programming. Modelica and other modeling languages allow us to describe component-based decompositions and link these to dynamical simulations. R and other software provides tools for statistical modeling.

The real value of CT is that it provides a context in which all of these can interact, and a rigorous language for defining and analyzing those interactions. Now we have a chance to formalize entire toolchains and workflows: we can agree on a graphical model, produce from it a semantic (logical) model and populate it with data from an existing schema. We can use that data to derive a dynamical model, and transform this into a computational simulation before piping the results to statistical software for analysis. This entire process can be structured by categorical models.

This indicates why systems engineering offers an ideal test bed for the emerging discipline of applied category theory. First, there is no avoiding the need to employ formal methods from multiple disciplines. The details of our system exist at different scales and layers of abstraction. The need to interface between many groups and researchers generates many demands: precise language to prevent misunderstanding, intuitive (e.g., graphical) representations for easy communication, and structural modularity for putting these pieces together.

Today, CT can supply plausible suggestions for meeting all of these requirements and more. However, much work is required to turn this promise into practice. We can identify at least two important obstacles which have stymied the growth of applied category theory.

First of these is CT's learning curve, which is undeniably steep, but has become more gentle in recent years. New textbooks [16,22] targeted at scientists and undergraduates have made the mathematical ideas more accessible. New applications in areas like chemistry [7], electrical engineering [5] and machine learning [8] have broadened the base of examples to more concrete, real-world problems.

A more substantial obstacle is tool support. Today CT can solve many problems at the conceptual level, but there are few good tools for implementing those solutions. Outside of functional programming (one of the major successes of CT) most software is academic, and it is neither simple enough nor powerful enough to address system-scale demands. Addressing this deficiency will require substantial funding and a concerted effort to bring together mathematicians with domain experts to attack complex, real-world problems.

Fortunately, this requirement is less daunting than it seems. Because CT generalizes many other formalisms, we should be able to use existing tools to solve categorically formulated problems. By turning a category into a logical theory we can use an OWL theorem prover for validation. To analyze the behavior of a functional model, we can derive a Petri net for simulation. By projecting our categorical models back into existing formalisms, we can piggyback on existing tools and methods. The results of these analyses can then be lifted back to the categorical level for a holistic appraisal.

We envision an open, CT-based platform for information modeling and analysis. The platform should support modules for the various CT constructions (e.g., functors, colimits) and translations (OWL, SQL, petri nets), which could then be assembled on a case-by-case basis to address specific problems. In the long run, such a platform would be applicable across many domains, but to get there we first need to drill down and provide a proof of concept. Systems engineering is the perfect candidate.

## Disclaimer

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**Title of the Presentation:**

An introduction to the PSI (Product – Social – Institutional) Matrix Framework

**Synopsis:**

The PSI matrix is a framework for studying designing as practiced in the real world: framing and solving technical, social or organizational goals embedded in the existing socio-economic and institutional cultures and practices. Given the interconnected nature of designed products, knowledge and activities and their context, we should anticipate that understanding designing would require an elaborated model. Consequently, understanding designing involves mobilizing multiple knowledge sources, with different perspectives and diversity of participants orchestrated to achieve an effective outcome.

**Main References/ Further readings:**

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Subrahmanian, E., Eckert, C., McMahon, C., & Reich, Y. (2017). Economic development as design: Insight and guidance through the PSI framework. In *DS 87-1 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 1: Resource Sensitive Design, Design Research Applications and Case Studies, Vancouver, Canada, 21-25.08. 2017*.

Reich, Y., & Subrahmanian, E. (2017). The PSI matrix–A framework and a theory of design. In *DS 87-7 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 7: Design Theory and Research Methodology, Vancouver, Canada, 21-25.08. 2017*.

# DESIGNING PSI: AN INTRODUCTION TO THE PSI FRAMEWORK

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## Abstract

The PSI spaces are a framework for studying designing as practiced in the real world: framing and solving technical, social or organizational goals embedded in the existing socio-economic and institutional cultures and practices. Given the interconnected nature of the design product, knowledge and activities, we should anticipate that understanding designing is at least as complex as designing itself. Consequently, understanding designing involves mobilizing multiple knowledge sources, with different perspectives and diversity of participants orchestrated to achieve an effective outcome. We call the study of the PSI spaces the PSI framework. We introduce the PSI spaces, and their language resting on diverse disciplines such as psychology, engineering, economics, and sociology. We introduce some of its methodological tools; how the PSI spaces might be used to explain design challenges through misalignments of the spaces and how these misalignments could be resolved. The PSI framework has significant implication to the development of design science; it demands that design science be a trans-disciplinary endeavor, in need of a flexible community that will study it.

**Keywords**: Design management, Design theory, Organisation of product development, design science

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Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. nn: Title of Volume, Milan, Italy, 27.-30.07.2015

## 1 INTRODUCTION

Contemporary products are designed by people, from different disciplines, performing different tasks that require different perspectives, using diverse knowledge. To accomplish their objectives, these people operate in a particular way and interact with their extended lifecycle chain. The environment in which these designing processes take place changes continually; primarily, as a result of our previous designs that interact in complex, often unforeseen, ways.

Observed performance of designing in different situations, varies significantly, whether reflected in the quality of the product or the execution of the process and the natural and economic resources it consumed. What then distinguishes between the better and the worse forms of designing? Can we characterize which factors are central in a particular situation? Can we tell if we are in a bad situation or even beginning a downward slope? Can we prevent failure and succeed to reinvent ourselves?

It turns out that most of the tens of thousands new products introduced every year in the world fail (McMath & Forbes 1998). Further, there have been many studies that found numerous internal and external factors differentiating between the successful and failed projects; more than 80 according to Hauser (2001). However, most studies on the subject are not useable to practitioners: 'Many (managers in industry) are aware of the scientific literature that studies the antecedents and consequences of metrics in multi-firm studies. But to fine-tune the culture of their firm, these managers need a method that adjusts priorities based on measures of their firm' (Hauser 2001: 135).

Significant failures occur also in working systems after years of operation, resulting from the dynamic nature of our environment as well as the stagnation or deterioration of organizational systems.

One method to address such failures is to anticipate and prepare for them explicitly before they happen (resilience model). This is a *proactive* approach to preventing catastrophic failures – perhaps utopia sought by those developing safety-critical systems. Such a system is largely considered *technical* even if it includes operators or other users. Dealing with them is done through engineering, ergonomics and marketing. The system is designed by designers from different disciplines, using their knowledge to satisfy given or formulated requirements. The designers themselves, the way they interact in their organizations, or their social network, are not considered parts of the quality of the product and are certainly not mentioned in the product specifications.

The second method to address failures is to wait for systems to break down and then change them (reactive model) as well as the relevant organizational procedures and structure. This requires a reflexive organization capable of adaptation to changes in the environment. Considering the organization and the system it develops as an extended system, all factors become part of the specification of the extended resilient system. How then do we take such complex systems and understand their failures or successes?

Our long-term study of designing (e.g., Davis et al 2001, 2005, Konda et al 1992, Monarch et al 1997, Subrahmanian et al 1991, 1993a,b, 1997, Reich et al 1996, 1999) suggests that *all* designing of all man-made products have three common threads and that if these threads are woven carefully into a quilt, they support and nurture an endeavour, and if not, they lead to their demise or deteriorated performance. We call this quilt the PSI space and its threads the P (product) space, S (social) space, and I (institutional) space. We call the study of the PSI space and its ramifications – PSI Framework. This paper motivates and introduces the PSI Framework. Section 2 defines the PSI space. Section 3 introduces the PSI Framework and describes how the PSI space is used. Section 4 summarizes with future work and prospects.

## 2 THE PSI SPACE

Designing as described in the first paragraph, takes place within multidimensional contexts. Characterizing designing in the PSI space took almost 30 years to crystalize, through study and close collaboration with industry in addressing their design processes. The PSI space reflects the desire to understand real design processes rather than toy or laboratory design contexts. The characterization echoes observations made by others: Several management scientists have emphasized the importance of social, cultural and institutional aspects of design and production of products (Takeuchi & Nonaka 1986, Clark & Fujimoto 1991). Pavitt (2000) made the case that the assumptions of early evolutionary economics theories could not anticipate the failure of technology transfer to developing countries, as they did not account for the state of the countries' social and institutional skills and knowledge. In the domain of Open source software, Weber (2005) points out that not all open source projects succeed as

they are dependent on the organizational structures that manages participation and the co-ordination of the project. Here the product, the participants and the organizational structure are intertwined in determining the success and failure of the project. In light of these observations, our goal was to characterize the design problem in full, beyond the artifact itself. We have identified three aspects (spaces) that characterize the position in the space in which designing of a product takes place within its larger socio-economic-cultural context.

## 2.1 P – Problem/product-space[1] – what kind of product is being designed?

The Problem/product space characterizes what is being designed as a three dimensional space. The dimensions are disciplinary complexity, structural complexity and knowledge availability.

### *2.1.1 Disciplinary complexity*

Disciplinary complexity is the number of disciplines and their relationships that are required to understand and create the product. The notion of disciplinary complexity is important as for each of the disciplines there are models, vocabulary and languages that need to be stitched together to design the products. One can observe this trend from the industrial revolution to date. Machines and theory of machines were sufficient from mechanics point of view to build wide range of products and equipment. Even the design of these products required knowledge of production techniques, material properties and processing of materials, context of use and so on. In recent times, disciplinary complexity is increasing in many products. Cars are not just electro-mechanical systems any more. They integrate computer hardware, software and electrical and mechanical systems working together with ergonomics, environmental studies, sustainability, economics, law and other disciplines much more tightly. Each discipline plays a part in the whole of the product and the part and the whole needs to work together.

The relationships between disciplines are often intricate. Some disciplines share concepts and even governing equations (as presented in the IEKG, Reich & Shai 2012) and some are rule based or narrative based (history). A "purely" technical product, that involves 3 disciplines (e.g., brake system with mechanical, electronic and software), would be less complicated from a product with only 2 disciplines, technical and economics, for example, transportation for commodity distribution.

This suggests that disciplinary complexity is a model of the complexity of weaving the required disciplinary languages. While integrating disciplinary languages into a concerted whole, parts need to be maintained carefully to allow the depth of each discipline to bring its power and benefit to the whole design.

### *2.1.2 Structural complexity*

Structural complexity is the decomposition of the product or problem into parts and their relationships. Structural complexity is what Simon (1972) had in mind in his article on “Architecture of Complexity”. However, Simon’s notion of complexity is limited as it only deals with the idea of near decomposability and hierarchies for dealing with complexity. To address current models of structural complexity we would need to address the inter-dependence of the parts in their functional performance. An example from the evolution of cars is the difference between a car from 20 years ago and now. In current cars, the brake system, the engine control system and distance perception, which were left to the driver to resolve, are interconnected and do not form a simple hierarchical system. Products such as aircrafts have more tightly integrated subsystems and components that could better be understood as a network and not a hierarchy. A network of inter-dependent functions does not conform to near hierarchical decomposability making the system design a harder and complex problem in terms of failure modes that can be normal, emergent, and unknown (Perrow 1999).

### *2.1.3 Knowledge availability*

Knowledge includes formal, tacit and informal knowledge that are embedded in the models, theories and practice. Its availability for designing a product or service within an organization and outside it is another important aspect. If all knowledge is available, then the product requires no new searches for

[1] We use problem and product inter-changeability as we see design of process, policy, service and products as fundamentally a similar problem of design and implementation. Only the context and goals change.

knowledge; on the other hand, if not all the knowledge is available, the unknown part of the knowledge has to be generated and fitted into the puzzle. Unknown knowledge will not always fall under a single discipline; it will often cross disciplinary boundaries. The approach to dealing with different disciplines requires diversity of experiences and dialogue between them to bridge the gap. Filling the gap means also integrating the new with existing knowledge. This creation of knowledge has to be designed through either experiments, or specific research and development explorations. So designing of product recursively involves designing of the search and creation that is required to discover the new knowledge and its relevance for future products.

#### *2.1.4 P space summary*

All 3 P-space dimensions, moving from simple to complex, involve increasing quantity and relationship across them, whether it is product components, disciplines, or knowledge gaps and their relations. In addition, each of these dimensions themselves also trigger change in the other dimensions. Increased complexity in one dimension, tend to increase the complexity of the other dimensions, meaning, more the components, more the chances that multiple disciplines are needed and more the knowledge gaps that will emerge. Today's aircrafts are very different from the aircrafts of 50 years ago while the basic function has remained the same but they operate in a very different system of disciplinary complexity and technology (knowledge) availability space.[2]

Over time, a product/problem positioned in the P space could move along all three dimensions. For example, knowledge that is at the cutting edge, scarce, and not integrated with other knowledge becomes common practice; and product once innovative becomes obsolete. Historically, products tend to involve many more disciplines, and become more complex to reflect the changes in social needs and requirements that are imposed on the product. The problematic is that increasing complexity is not linear and new complexities add up creating unintended consequences and unforeseeable failures.

### 2.2 S – Social-space – with whom do we address the product?

The social space characterizes the social entity that attempts the problem/product space. It has significant effect on the outcome of designing; our characterization defines its three dimensions.

#### *2.2.1 Number of perspectives*

A perspective here is a "point of view" that is critical in executing product related activities throughout its life cycle. This idea of perspectives is interesting if one observes the evolution of computing. Early, it was all about computing algorithms, theory and programs that were the focus due to the use by narrow set of people. The idea of bringing the needs of the user perspective as the computer became individualized was first illustrated by Xerox and commercially by Apple. This has led to new field of design of user interfaces over the last 20 years. Consumer perspectives, maintainability and numerous other abilities are perspectives. There is no limitation on different perspectives even within a discipline. Perspectives are not just views form the disciplinary knowledge but also practical perspectives derived from practice as well as those affected by the product as it is being developed; the need for such perspectives is not often a priori known. Perspectives may interact with each other in complex ways.

#### *2.2.2 Inclusion*

The definition of the inclusion in the social space as limited or open is in terms of the inclusiveness of participation of the different perspectives. For example, if current participants in the social entity believe that in the problem space all the knowledge is available to them, they will assume a limited inclusion (closed). In the case of lack of availability of all knowledge, the social space should assume an open world characteristic with the lookout and intension to possibly extend the perspectives and the

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[2] John McMasters (2004) pointed out that the number of disciplines needed to create an aircraft changed dramatically from aerospace, material and mechanical engineering to the need for environmental, computational, chemical engineers and others. He also makes the case that the future of aircraft design would require people with cross disciplinary skills who he classed "deep generalists" in greater number than ever before. His estimate was that it has to go up from 10% of workforce to about 40% of the workforce.

respective languages that need to be incorporated. To illustrate, if the problem is to optimize the route from a point A to B and all the knowledge is available, a closed world with only optimization experts and the corresponding mathematical language is sufficient to address it. However, if the problem is to figure out the complex interaction between road traffic, pollution and potential health effects of a traffic interchange in a neighborhood, the problem requires an open social space with respect to the people and skills to be included in both defining and solving the problem. In open source software development, the social space is inclusive in the sense of self selection – anybody may choose to join the development effort but need to establish their credentials to be integrated (Weber 2005).

#### *2.2.3 Capabilities/Skills*

By skill we mean an ability to do something such as disciplinary thinking, creative thinking, critical thinking, and system thinking. Similar to a product having parts, a design process has tasks requiring different skills: careful management of requirements, creative generation of concepts, systematic analysis and test of concepts, and their selection. Skills could be considered as parts in the whole process. One could think of this dimension as a composition of notions of competence, capabilities and skills in business and evolutionary economics literature (Dosi et al 2002).

#### *2.2.4 S space summary*

As in the P space, the S space has 3 dimensions that involve increasing quantity and relationship among them. A change in one dimension often triggers change in the other dimensions. A need for additional perspectives or skills will probably lead to opening the space to more participants. Inclusion of existing participants with new perspectives or skills might prevent the affordance of additional knowledge and it would have to be traded off against time or other resources. However, in the design of a product, non-inclusion of a perspective can lead to failure of the product. Examples are many in the literature, and in the case of inclusiveness of the knowledge of the user, Von Hippel (2005) has made the case for its necessity in his work on democratizing innovation.

### 2.3 I – Institutional-space[3] – how do we work it out?

Assembly of participants with the right skills that cover the needed perspectives to develop a complex product that combines numerous disciplines with state-of-the-art knowledge is insufficient for success. Key to implementing any realization of a product is setting up the rules by which all the participants will work for an extended period of time. A complex product, requiring extended participation with multiple perspectives, requires flexible procedures that allow for continuous evolution, maintenance of shared memory, evolution of the team, and the evolution of the product requirements. It actually requires that the rules allow procedures to evolve in response to new situations. The 3 dimensions of the I space below characterize the rules of the system that govern the S and P spaces.

#### *2.3.1 Ties: social network*

Social networks are characterized by the strength of their connections; weak or strong (Granovetter 1983). Weak ties are characterized by the small number of transactions with very low exchange of knowledge and co-operation between the parties. Weak ties are often market-based ties but could also reflect weak knowledge connections within a firm due to institutional routines, processes and structures. For example, in the days of sequential engineering, the ties between different departments were weak as the knowledge transfer and its reconciliation was not made routine in the process. In the transition to concurrent engineering, the ties were made strong by changing the process of knowledge exchange and reconciliation between different functional departments (Clark & Fujimoto 1991). Strong ties require (and are created by) procedures and commitment to communication and sharing.
One can see similar differences in the strength of a network of suppliers. For example, the Japanese have four levels of suppliers who range from providing parts as per standardized design to those who co-design characterizing the nature of interactions and the transactions that are based on the needed level of knowledge exchange (Liker et al. 2006).

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[3] The use of the term institution here may raise objections as it does not seem to distinguish between organizations and institutions. We have chosen the term Institutions to include both kinds of structures as from a design point of view they deal with different kinds of products/goods (Ostrom 2005).

Existing ties are challenged in contemporary practice of mergers and acquisition where organizations move from one context to another. In some cases, transition is made slowly and in others a revolutionary change may destroy the company. Example such as the Chrysler and Daimler merger and others provide evidences of failure to achieve organizational alignment while the Nissan Renault alliance has worked well to the advantage of both companies.

#### *2.3.2 Knowledge accessibility*

Within an institutional structure, the knowledge is dispersed in different individual and different parts of the organization. These are resident knowledge in the form of institutionally codified formal knowledge, other informal knowledge that is tacit, and knowledge that is recorded in personal notes, etc. While this knowledge is accessible, it is often not accessed as seen in the contrast between over the wall engineering and concurrent engineering. In many organizations, people at the cross roads of information flow have unique knowledge at the interfaces (Davis et al 2005). It is only accessible through them as it is not often public. This analysis demonstrates the recurring phenomenon we find in the previous dimensions. They all have a "quantity" and a structure associated: number of parts and their interconnections, number of disciplines and their integration, inclusion/exclusion but also the way these inclusions are distributed among participants, perspectives, etc. Here also, knowledge accessibility manifests itself in the connections between perspectives and disciplines.
A similar problem can occur in networked organizations at the interfaces between original equipment manufacturers (OEM). The knowledge of the supplier is only accessible to the OEM under contract with the supplier and otherwise, inaccessible. The arguments made for product modularity are the separation of knowledge and the ability to outsource and operate without the detailed knowledge of the module; that often does not work due to overlapping knowledge (Dosi et al 2004, Hart-Smith 2001).

#### *2.3.3 Institutional complexity*

The institutional space is different from the social space as it concerns the design and use of rules, norms, routines and other formal and informal organizational structures. In the case of markets, the rules will be the market rules and regulations that govern the market. Within an institution, the rules and norms can both hinder and enhance the possibility of using the social space. For example, the American car companies and Japanese Car companies had more or less the same capabilities in the seventies when the Japanese firms started making major inroads into the American market by improving the quality of the products far beyond the American products. The key difference between them was written up as over the wall engineering vs. Concurrent or Simultaneous engineering (Clark & Fujimoto 1991). The fundamental difference was in the institutional rules and norms of how information and knowledge was processed and exchanged in these organizations. Movements such as Quality circles, Quality function deployment, that changed the dynamics of routines in Japanese organizations for fast elimination of failures and errors in the design and production processes were the key.

#### *2.3.4 I space summary*

The economist Ostrom (2009a) argues that design of institutions should be done in the same manner as engineers deal with complex products, i.e., using empirical and theoretical tools. Her work on institutional analysis and development of management of public goods has led to a grammar for analysis of such public institutions and to describe the potential design of new institutions. While Ostrom (2009b) is talking about public goods, our attempt here is to use her framework on design of institutional structures to other types of goods. This view makes designing recursive as we need to design effective organizations to be able to effectively design products and often institutions to regulate the behavior of the producer of these products. But to be more precise, all the spaces are interlinked in a recursive sense with respect to designing. The product may be managing the use of natural resources, public infrastructure development and many other products and services that the governmental, non-governmental and private organizations provide. In all of these cases, the product space, the social space and the institutional spaces are linked.

# 3 THE PSI FRAMEWORK OF DESIGNING

We have shown how three spaces characterize the scope in which designing takes place in a situated place and time along with their history, culture and geography. Place and time define a broader social, political and cultural contextual frame (situatedness) within which the act of designing is defined and located in these spaces and evolves over time. The study of these spaces and their implications to designing research and practice define the PSI framework.

## 3.1 Methodology of the PSI framework

The PSI framework is both empirical and analytical. It rests on observations of design cases and their analysis by multiple research tools available primarily in engineering, social sciences, and management. These include simulation and modeling of various aspects of the PSI framework. Its central objective is not only understanding designing, but improving designing in practice. In fact, there is no separation between the two. Understanding designing comes from engaging and intervention (Reich et al 1999, Subrahmanian et al 1997, Davis et al 2001, Reddy et al 1997). Practice is the ultimate validation of new knowledge about designing.

The PSI framework is part of the science of the artificial, it is designed! If we want to continue designing and improving the PSI framework, we have to treat it as a product and understand its place in its own PSI space just as we claim that any designing act can be described in the PSI framework. Figure 1 illustrates this analysis. Part (a) depicts the 3 PSI spaces; it is part of the product generated by the PSI framework as described in Section 2. Part (b) depicts the location of the PSI framework in the 3 PSI spaces. It is neither common nor easy to analyse an entity with itself but it demonstrates that the framework is reflexively consistent if it can be done (Reich 2006). In the P space, the PSI framework as an artifact is very complex, consisting of the 3 spaces but also of all the related knowledge and tools used to advance it; these are constantly changing.

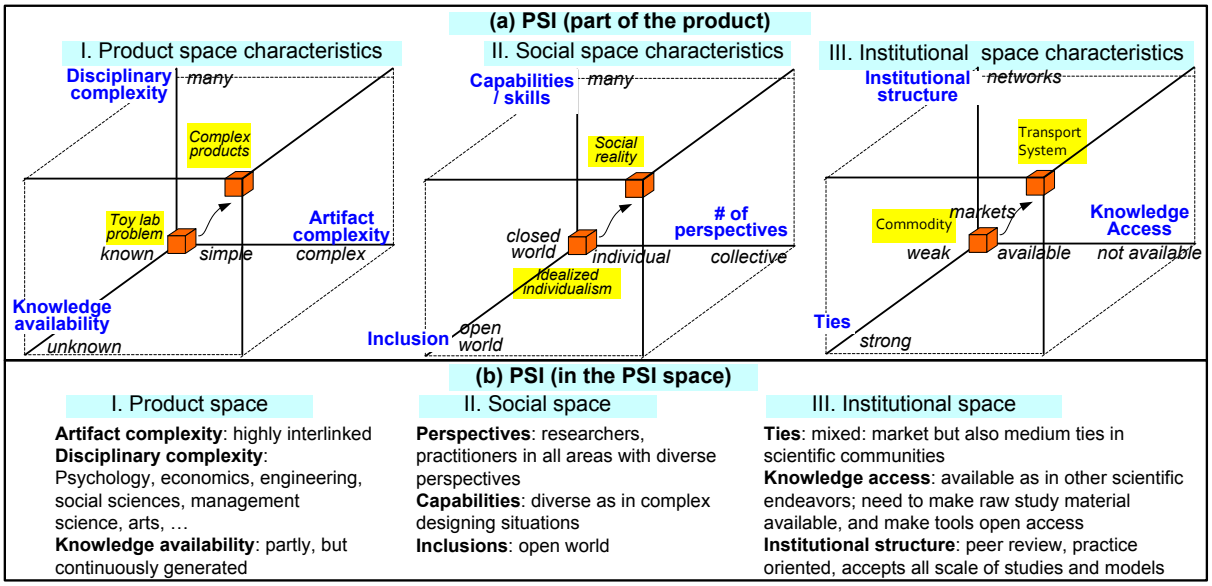


*Figure 1: Designing and the PSI space*

The PSI framework involves the collaboration between numerous disciplines including: psychology, anthropology, sociology, economics, management, history, and art. In fact, there is no discipline that could not contribute. As a scientific field, knowledge about the PSI framework is available in different sources but much practical experience is proprietary and inaccessible. One could argue that knowledge about, and the ability to move in the PSI space results in competitive advantage to an organization.

In the S space, the PSI framework requires multiple perspectives to develop, including researchers, design practitioners, users, and all other design stakeholders. The skills required are equally diverse in order to observe, analyse, document, synthesize, implement and test creatively and systematically the products generated in the PSI framework. As a research program, the elaboration and population of theories and practices in the PSI framework will be inclusive of multiple disciplinary perspectives.

In the I space, the PSI framework as other sciences works through mixed ties. Theoretically, the ties are both strong and weak, allowing relations or research activities to form in an ad hoc manner while social networks such as scientific societies and other alliances create stronger ties. As in science, access to knowledge is supposed to be given but as significant part of the PSI framework is case studies, some knowledge might be proprietary. Science culture also prevails in the PSI framework; it is a comprehensive way to study the varieties in design. If we call the study of design 'design science', then the PSI framework is part of design science.

## 3.2 Using the PSI framework

The world is littered with failures of products, services and policies. Some could be explained by missing key technological elements, some by missing expertise, outsourcing, crowd sourcing, bad knowledge management practices, or loss of expertise, and others by organization culture, leadership, or poor supply chain qualities. In most cases, studies are conducted on sample of cases, attempting to reveal key indicators by analyzing the dependence of parameters on independent set of inputs. Such results are difficult to apply in a particular situation that does not fall well into the models (Hauser 2001). They might also be limited since they take a narrow view of the problem into account.

### *3.2.1 Location in the PSI space and explaining failures and successes*

Given that the dimensions are not directly measurable, we can only relatively locate an organization in the space and characterize it. Extensive studies might be necessary to form a more precise characterization. For example, information flow analysis can be used to detect the organization's implicit structure and its match with organization rules; supply chain analysis to detect the nature of ties with collaborating entities; product planning to understand the extent of disciplines that might be involved; and technology forecasting the maturity and availability of future technologies and methods.

*All aspects of a design situation must be aligned*. A startup company working in a high paced product market must move fast by limiting its inclusion, managing only the necessary perspectives, and have the culture that foster quick turnover of ideas, knowledge, and decisions. Some of these choices introduce risk due to missing perspectives or even lack of maintaining shared memory. When such a company begins to generate revenues and builds customer portfolio, different culture has to be exercised, ties should be developed based on the nature of the product and new perspectives such as marketing or maintenance, become critical. Such evolution is natural (Dosi & Nelson 2002); it even occurs within a large company since its environment is changing and the location in the PSI space is relative rather than absolute. If the company is not able to evolve, it often does not survive as it does happen with mature firms where the routines and norms are already set in place. They face a harder problem of evolving to new routines and structures due to a variety of resistances. This behavior can be seen in the supply chain behavior of American Car companies vs. Japanese Car companies. Liker & Choi (2004) show that even though the knowledge of operation of the Japanese car company institutional structures is known to American Car companies, they continue to operate in more or less the same as they always did before. Their strategic focus on cost in the short run has not allowed them to change the routines to take advantage of learning and long term cost advantages that Japanese companies seem to exploit. Another example is Polaroid that had very advanced sensors and digital technology for it to enter the digital camera market but did not in favor of its existing market, and lost.

### *3.2.2 What binds or breaks the alignment of PSI spaces?*

Designing a product requires an orchestrated balanced dance, with many diverse participants in a highly multidimensional interconnected space. This requires bridging many gaps between different entities pushing in different directions. This is a fragile situation prone to failures as any bridge needs maintenance and upgrade to sustain environmental changes. These changes tend to have a cascade effect. These bridges have to be flexible, malleable; they need to be maintained and traced through their evolution. These bridges consist of words, concepts, language elements as well as their assembly into sentences, ideas, models. This embedding of inner structure of parts and wholes and their interrelations manifests everywhere. The problem of decomposition and synthesis operates in different dimensions across the spaces leading to conflict between division of labor and knowledge.

This situation is further aggravated in a globalized context by the fact that the modules themselves may be produced in different countries and cultures adding to the socio-linguistic and competence alignment that is required around the cognitive artifacts that serve as boundary objects to mediate

among the parties. The striking examples of failures are in the aviation industry. Airbus in its production of A380 had problems because the models produced by one version of the software were not compatible with one of its supplier's version of the same software (Wikipedia 2014).
In the case of Boeing 787, the extensive outsourcing of its components led to the delay of the release of the aircraft. The institutional structures and routines created to deal with their outsourcing model were not compatible with knowledge structures required to integrate them leading to mismatches in understanding the needs and requirements across different suppliers (Hart-Smith 2001). A lead engineer in Boeing recently admitted that Boeing had to have the knowledge of all the parts and their manufacture even that of others to manage the design and production of an aircraft (Hiltzik 2011).
A different failure, often discussed in the design community, is the lack of transfer of many results from research into practice, representing two social communities with different cultures. Using the PSI framework, we can explain how an approach like the Fraunhofer Institute (2014) succeeds in bridging the culture of these communities. The Fraunhofer Institute, a network of 67 institutions distributed all over Germany and outside it, presents itself as a large-scale example. It has a matrix structure with overlapping competencies that are applied to different technological areas. The different institutes may compete, collaborate, and complement each other in different projects providing a mix that evolves to be highly resilient. They maintain their organic structure of routines and skill development healthy and interconnected. They work well with local industry creating strong local ties. They work through permanent cultural mediators in different countries to bridge cultural and market orientations. All these make the Fraunhofer Institute a highly well aligned, and continuously evolving model of change in the PSI spaces.

### *3.2.3 Establishing alignment*

One cannot simply look at a design situation, determine its location in the PSI space, and analyse its efficacy and deficiencies. Such insights come from engaging with a variety of research, intervention, and participation tools which are part of the PSI framework (section 3.1). Such tools are also the key to addressing misalignment by analysing the alignment status, proposing a change, and enacting it. Alignment does not work in large steps. While aligning, one has to keep in mind that ultimately, the changes are to be implemented in practice. Hence, there need to be a plan to gradually bring an organization and a social setup into harmony with a given problem. One can implement this strategy by promoting changes via games, scenario analysis and other methods that encourage exploring alternative trajectories and promote reflexivity to be able to anticipate changes and implement them (Meijer et al. 2014, Subrahmanian & Reich 2006). The guiding principle of the PSI framework is its reflexivity, any particular outcome that needs to be achieved, even reflection, requires the use of the PSI space and its methodological stance.

## 4 EPILOGUE

We have only begun to explore the PSI framework, introduced its terminology and some of its methodological approach and benefits. While its development rests on over 20 years of study, as additional studies of design situations accumulate, whether successes or failures, we will start to uncover patterns of successes, create models and theories to explain and predict outcomes of using the PSI space. In view of reflexivity, the PSI Framework involves extended participation of disciplines outside of traditional engineering design and requires cultural flexibility to evolve into a broader enterprise that could seriously address contemporary design challenges.

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# ECONOMIC DEVELOPMENT AS DESIGN: INSIGHT AND GUIDANCE THROUGH THE PSI FRAMEWORK

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## Abstract

Economic development is aimed at improving the lives of people in the developing world, and needs to be carried out with design at its heart, but this has often not been the case. This paper first reviews dominant approaches to economic development including the use of subsidies or the creation of markets and demand and the testing of initiatives using randomized control trials. It then introduces 'development engineering' as a representative engineering design approach to engineering and technology in development before presenting the view that successful development needs to involve continual learning through innovation in context. The PSI (problem social institutional) framework is presented as a basis for guiding such development as a design activity, and its application is illustrated using examples from India of the unsuccessful introduction of new cooking stoves and then both successful and unsuccessful approaches to rural electrification. A 2-level approach to PSI is taken, in which the lower level represents daily operation of communities and the 2nd level represents the development project including addressing misalignments between the different PSI spaces and levels.

**Keywords**: Design theory, Social responsibility, Participatory design, Economic development

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Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol. 1: Resource-Sensitive Design | Design Research Applications and Case Studies, Vancouver, Canada, 21.-25.08.2017.

## 1 INTRODUCTION

In his book "The Sciences of the Artificial," Simon proclaimed that any person who is involved in changing the state of affairs to a new desired state is engaged in design (Simon, 1996). Even though Simon pursued the idea of the science of design as a decision making and problem solving process, he also alluded to social planning as an activity with evolving goals that may not be amenable to his original idea of problem solving. As it so happens, the vast majority of problems in the developing world involve a combination of the introduction of technology and social planning. In this paper, we take an approach to design that is centered more on the social interactions and socio-economic context in designing and on solving the problem that evolves over time.

Economic development, in particular in the developing world, is an activity aimed at changing and improving the lives of the people, which makes it a design activity and would point to design as a vehicle of economic development with engineering design at its heart. However, the reality is not so simple. Many well-intentioned engineering projects fail to deliver the hoped-for improvements and many development researchers overlook design as an agent of change that can be directed to deliver improvements and privilege policy change or social change in engineering projects.

This paper compares three possible approaches to economic development: the current dominant economic models of development, an engineering perspective on development, and our expanded notion of design that includes the problem that is addressed and its social and institutional context together in a single framework called the PSI framework. To prepare the reader for the comparison, we first provide a brief overview of the dominant strands of thinking in economic development. We also identify the lack of engineering content in the discourse on economic development in general. Further, we make the case that, even when adopted, current engineering design approaches to technology and development are inadequate in addressing development problems. We use our framework to explain failures and successes in economic development projects that have involved technology, using as examples cases from India of biomass cookers and rural electrification.

In the paper, we view engineering as an activity that has a specific goal to satisfy a need or desire, and that it may involve adapting an existing product or a service or creating new technology that is situated in a particular social and institutional context for a specific audience either through a market or as a public good. While the components of the designed artefact or service may be captured as quantifiable requirements, the system and its behavior in context will transcend the purely technical requirement of the components themselves.

## 2 ECONOMIC DEVELOPMENT AND DESIGN: DOMINANT VIEWS

In the vast literature on development, there are different strands of development theories and philosophies. The dominant ones come firstly from Jeffery Sachs (2006) and his adherents, whose goal of eliminating poverty is through distribution of funds to overcome the poverty trap, and secondly from William Easterly, who advocates creating conditions for markets to emerge leading to demand for human labor leading in turn to alleviation of poverty (Easterly, 2008). In contrast to these top-down theories a new bottom-up model of development promoted by Banerjee and Duflo (2011) uses randomized control trials (RCT) as a way to understand the behavior of the poor for the creation of targeted policies to address specific problems such as deworming of children in Africa (D'Aoust, 2014). RCT is criticised as reductionist, and failing to take into account the sociological, economic and psychological needs and capabilities of the population that is targeted for intervention (see Woolcock, 2013; Reddy, 2012). While RCT can provide internal validity, it does not provide external validity in terms of functioning services and products (Woolcock, 2013). All of economic development is about changing the multi-dimensional state of the world for the poor or underprivileged to a state where poverty is not a handicap in their functioning as productive citizens. More generally, while all of these approaches aim at changing the state of the system through interventions, they are often viewed as design or engineering problems not situated in context but as requiring transfer of dominant designs from developing countries (Heeks, 2002; Tongia, 2006). An engineering and design perspective requires internal validity of the methods to be aligned with the external validity or performative aspect of the artefact that was designed; that is often the missing link in development efforts.

Albert Hirschman, a non-conformist economic thinker and development economist, questioned the logic of self-interest capitalism as the path to general welfare (1977) by arguing that the model of capitalism

that is based on rational calculation was not even consistent with Adam Smith's appeal because it ignored the role of sympathy, honor, friendship and collective interests in the rise of modern form of capitalism. Based on his vast experience in working in development projects, Hirschman deplored the idea that, from outside, using the model of self-interest, one could help people to become economically developed. He rejected the 'one-size fits all' models of development and taking up one problem at a time as that would suffer from the problem of interdependence (Hirshman, 1977). He contended that it is only through experience, trial and error and creativity that we encounter and overcome the unexpected. For that reason, development problems have to be solved with local communities, taking into account their knowledge and aspirations, and not through externally calculated rationality. Such rationality apparently renders the problem easy, removes doubt and experience and makes it as if all problems are the same, it may thus erroneously be seen as a 'silver bullet' to make lives better.

## 3 ENGINEERING AND DEVELOPMENT STUDIES

In a recent article by Robbins et al. (2016), the relationship between engineering and development (or lack thereof) is explored. In their thorough analysis of the history of development studies, they trace the thinking in development from its origins in 'development science', which assumed that development occurs solely through science and that the promotion of science in developing countries would lead to development. This is based on the prevailing post-war belief (or myth) that the path to development is from basic science to applied science.

Robbins et al. point out that engineering has been largely absent in these discussions and one would wonder why technology and innovation have a place without attention to engineering and design. This perspective is only meaningful if one believes that development is the transfer of technology and innovation from the developed world to the developing world, in which case economic development is nothing but empowering the people of developing countries with some substitutions of technology that already exist in the developed world.

Recently, Development Engineering (DE) is being viewed as an answer to the need for a framework for the role of engineering and technology in developing societies. As Robbins et al. (2016) point out, the goal of DE, as envisioned by researchers at UC Berkeley and other practitioners, is “applying economic and engineering research to the problem of poverty” (Nillson et al., 2014). However, there is no clear definition of what DE is and what its goals and focus are beyond technology and innovation transfer; the role of design in DE is also not clear.

Engineering design itself is also often very narrowly conceived, most often again with a focus on technology. It has been expanding the scope of the viewpoints that it acknowledges, for example by the explicit acknowledgment in the form of 'design for X' of manufacturability, recyclability and other 'ilities'. This extension has led to the emergence of life-cycle engineering approaches, that consider the impacts of the whole life of the artefact from conception to disposal, but the focus remains technical and does not include the socio-economic context, processes and institutional structures.

In addressing technical aspects, the current dominant discourse in engineering design is also often limited to methods and technology development for the use by the mass customized consumer from a physical and digital product perspective. Such an approach is not feasible for all products that are public, private and common pool resources for a population of in the order of 1.2 billion people as in India. Transporting technology in a non-contextual manner, propagating the idea that what is good for us is good for others, is hubristic and imperialistic.

It is noted that only 15% of all 'information technology for development' projects succeed, all others are partial or total failures (Heeks, 2002, 2008). Recently, Toyama (2015) makes the observation that technologies are not the panacea to development unless applied along with social and institutional change. The most common set of failures that have been catalogued in the literature have assumed that technology would work irrespective of context and can just be 'dropped in' for people to use or managed with top-down planning without any concern for the local needs/participation, narrow perspectives (both macroeconomic and microeconomic) and ignorance of history and social customs. These examples illustrate that for any theory of change, “the intent of the design” has to be technological, social and institutional. Unfortunately, this continues to be ignored because of professional practice that is present with its biases, history and economic ideology.

Engineering design is typically based on existing products as a means to reduce risk, cost and effort in product development. New technology is typically introduced into existing technology in a controlled

manner, after it has been developed either in supplier companies, in R&D departments or in universities and slowly matured to a point that it can be brought into a product at an acceptable risk. In the development literature, the distinction between engineering innovation and product development is not drawn up clearly. Product development processes are design processes, which are characterized by a co-evolution of the problem and the solution whereas R&D style engineering often pushes the technology. In design processes there is a clear understanding that the needs of users need to be understood and responded to in a product, even though many processes are still looking to find the solutions in a refinement of the current technical solution. Product development also has numerous methods and approaches, such as platform architecture or customization, which could usefully be deployed in an international development context when negotiating the boundary between designs created in the developed world for the developing world, but also in the developing world for their own use or for export.

If we have learnt something from being engineers and designers, it has to be the lesson that we solve problems by combining our and others' experience in the context of their lives that empower them and sustain them in the long run. This requires not just the artefact being designed, but also the social composition of experiences and capabilities and the creation of new institutional mechanisms that is reflexive to respond to the unexpected, for creativity and innovation to blossom and not be crushed by a unified, sterile model of development.

Engineering is not just the design of innovative artefacts, it encompasses design, manufacture, installation and maintenance of sustainable solutions that produce value for society in the long run. Engineering is not just about creating knowledge for the sake of knowledge as is claimed by the logic of science, it is about achieving some goals that address social needs and is transdisciplinary, where the theory of the artefact that is created is the theory of its functioning in a socio-technical context (Monarch et al., 1997; Vincenti, 1990). It requires trial and error and is contextual and confronts the unexpected with creativity and innovation. Engineers with their devices not only create change in the appearance of an artefact but change the nature of routines of people in their daily lives, social interactions and institutional structures in which they function. They are subject to constant revision and subject to changes in context and at times beyond context due to arrival of new technologies. They change the context and the context changes them.

This was exactly Hirschman's view of economic development: a fluid, complex adaptive and reflexive approach that continually learns and corrects itself through creativity and innovation in context. It is context-sensitive and explains that unexpected situations require a response that is creative and innovative. Both are complex, adaptive and reflexive in nature that acknowledges temporary closures and the presence of 'known unknowns' and 'unknown unknowns' that appear in unexpected forms.

To address precisely the complexity of engineering design in context, we adopt a framework that extends it to address the necessity for a holistic view of designing. We elaborate on this framework in the next section.

## 4 PSI FRAMEWORK

We have seen that design is a complex activity that takes place within a rich context of interacting conditions. In an attempt to understand these conditions and to use this understanding to inform design activities we have created the Problem Social Institutional (PSI) spaces theory of design (Meijer et al., 2014; Reich and Subrahmanian, 2015, 2017). The motivation is to bring the diverse influences that impact upon design – economics, engineering, management, psychology and sociology – together in model that is rich enough to encompass all of these influences (and more) but also simple enough to be useful. The model poses questions about three spaces of design as follows:

- In the *problem space* the question is asked "what is being designed?" This space describes how engineering, marketing, R&D, the sciences and other disciplines come together to formulate the problem to be addressed and to transform it into a designed artefact.
- In the *social space* the question is asked "who are the people who are stakeholders in the design?" Exploration in this space aims to understand the motivations and aspirations of those involved in the artefact – from designers through users to maintainers and suppliers.
- In the *institutional space* the question is asked "what is the institutional context in which the design is conceived, implemented and operated?" Understanding this space allows economic, managerial,

organisational and political contexts – e.g. the influence of the involved companies and national and local organisations – to be understood and that understanding applied in the design process.

Each of the spaces, P, S and I, is further characterised by several dimensions. These are described in more detail in (Reich and Subrahmanian, 2015), but in summary:

- In the P space the *disciplinary* dimension describes the disciplines that are required to understand and respond to the problem and their relationship with each other; the *structural* dimension describes the way the problem and artefact space are decomposed in order to manage the complexity of the design task, and the *knowledge* dimension describes the knowledge available and needed to address the design task.
- In the S space the *perspective* dimension describes the diverse social viewpoints that are brought to bear on the artefact, and their interactions with each other; the term *inclusion* is used to describe the extent to which the social space is closed or open to multiple perspectives; the *capabilities/skills* dimension describes the participants' attributes needed to execute the design.
- The I space represents the rules, methods, procedures by which all the participants will be designing the product. In this space, the *ties* dimension describes the connections between the actors in the social network designing the artefact and their consequences for the design. The *knowledge accessibility* dimension describes how those actors can access the knowledge available in the various participating groups and organisations. The *institutional complexity* dimension describes the rules, culture, procedures and other formal and informal organizational structures.

In all the spaces, a change in one space often triggers change in the other spaces. For example, bringing more perspectives or capabilities in the social space may lead to defining the problem better, not only in more detail but also with entirely different focus. This may lead to a more complex or simply better solution in the problem space. In turn, understanding that the problem is complex, requiring a complex solution, may lead to using additional procedures to tame this complexity in the institutional space. In contrast, if a complex problem requires a quick solution as part of the problem definition, it may not be done by the organization if its processes and rules do not allow for cutting corners. In the terminology of PSI, the spaces need to be aligned. Failures and successes are closely tied to the alignment of spaces, as we will illustrate using the following examples of attempting technological change in a developing country context. Misalignments that arise due to various changes must be handled by redesigning the PSI spaces. This is best represented by a 2-level PSI framework where the lower level represents the daily operation of the organizations, community or an extended context and the 2nd level represents the development project including addressing misalignments. In the 2nd level PSI, the problem framing P' involves all P, S and I spaces below as shown in Figure 1. Since solving the misalignment is a design problem, it is clear why it requires its own PSI representation.

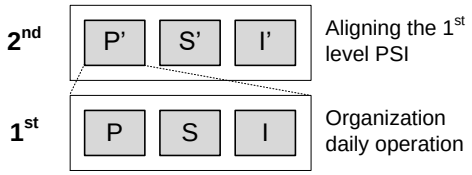


*Figure 1. Aligning PSI spaces with a 2nd level PSI*

Conceived in this way, the PSI framework allows framing any design challenge and specifically a development project and through this framing, focus on the aspects that need change. These may be a new or modified product or service, with new or existing technology (P space), a change in organizations or society (I space), or a change in people capabilities and skills (S space). As stated before, identifying one or several necessary changes may lead to others due to the need for alignment.

## 5 CASE STUDIES OF ECONOMIC DEVELOPMENT AND PSI

In this section we take up two cases of technology-centred efforts in the developing world context, in each case in India. The first example is that of biomass cooking stove, directed at the poor who are the primary users of biomass for cooking and the second case is a solar-based rural electrification problem addressed by the Indian central government and by a local entrepreneur.

## 5.1 Biomass cooking stove

### *5.1.1 The case*

Many people in India, especially in rural areas, rely on the burning of wood to cook their food every day, with implications for health and safety and pressure on wood supplies. The traditional cooking stove in India was made out of mud and bricks with an open mouth and opening for feeding the fuel. This has been used for centuries and is very smoky, leading to health problems especially for women, who are also the primary collectors of firewood as part of their daily life. 76% of rural households and about 26% of urban household use these stoves, and there are close to 260 million households in India (Hude, 2014). The very limited impact of attempts to introduce improved wood stoves in India is a simple example of dramatic failure with respect to technology and development (Khandelwhal et al., 2016). The implications of clean burning (minimal smoke), high heat efficiency biomass stoves as substitutes for traditional wood burning would be with respect to health, better efficiency stoves, and lower CO2 emissions. However, for a variety of reasons the widespread adoption has failed.

The goal of all cooking stove projects was to create a better stove that would minimize household smoke pollution. There are two primary types of stoves: natural draft and forced draft stoves. Forced draft was primarily provided electrically using batteries for energy storage. These stoves vary in terms of continuously-fed and batch-fed fuel mechanisms. Attempts to introduce these stoves have been made by different institutions, government agencies, NGOs, international agencies and corporations. The studies show that women do not use these new stoves as they have been developed to provide a one-size-fits-all model that does not take into consideration the cooking habits of daily life of particular regions. The women also did not use the new stoves because they now have to buy the fuel for them whereas formerly it only took time to gather firewood. The efficiency in cooking of the meals that are traditional to a region in terms of time to cook is also a very critical factor in their adoption. In effect, the concerns of the women are in the totality of their daily lives and their ability to maintain the stoves in the long run. The kind of shelters the users were living in and the ventilation facilities varied quite a bit across the households targeted. The cost of the new stoves, financing for the stoves, institutional support and maintenance, the supply chains and other aspects were not worked on with the communities. Besides, there are institutional barriers including subsidies for kerosene and LPG that distorted the market. All of the experimental new stoves have been based on an incomplete conception of the problem of designing the stove, viewing it as a technical task without a holistic perspective.

### *5.1.2 Interpreting the Bio-mass Case study with PSI*

The problem of the cooking stove is a classic problem in design and development: development as ownership of a new designed artefact that makes your life better or even gives freedom from drudgery. The design did not achieve the goal. Viewed from the PSI perspective (see Figure 2), we use 2 levels to explain this case. At the 1st level we describe the daily life of the community, using the product; here the stove but in any other development project, it would be another product. Without any additional step, it is clear that in order to execute the project, there may be a change in the way the community operates. If so, the community might in time need additional skills to operate and manage the solution. It is clear that if these changes will conflict with other needs, a cascading change process will ensue. In effect, the development project needs to be framed in P' as consisting of the whole 1st level: the way members of the community use the product for their purpose and the issues they have with this (represented by the P space), those in the community involved in the operation (S space), and the rules and customs governing the operation (I space) and extending to other life functions (P space). The problem in the P' space is to change or develop all P, S, and I, in tandem and in alignment to each other. The development project had to be executed as a 2nd level PSI to take this perspective. Such setup immediately calls for enlisting professionals, experts in local culture; but even this may be insufficient as in this case because the local community members have to be part of the development team - they are the sole experts in their daily lives! In reality, the project was executed very differently. The P' space itself was conceived by engineers and scientists (S') far away from the location of use, thereby not involving members of the S space in defining the P' space and not understanding any of the issues in the I space. Members in the S' space considered the P space only in framing the P' space, a violation of the principles of 2nd level PSI described before. Quite a variety of stoves have been constructed with the same or similar S' beyond the experiment being conducted. The ignorance of the S and I spaces in framing the P' space led to considering a single solution to all contexts where in fact, each should have been modelled as a separate

1st level PSI. If the problem was modelled correctly, each context, including a variety of implementing NGOs or remote corporate or government organizations and their practices that populated the S and I spaces, would have its own 1st level PSI. This would have led to addressing such a multitude of issues with much better technological, social and institutional design. Such a model would have led to sharing knowledge between these contexts that otherwise was lacking because it had no relevance in framing the problem. A solution that only changed the P space would create misalignment between the PSI spaces and made the solution unsustainable. There was no knowledge in the S' space to change the S or I spaces; therefore, no sustained supply chains were conceived as part of the solution, no changes in the Government policies (institutional) were ever contemplated, and there were insufficient funds to even attempt to maintain and sustain the new situation. In effect, there was no thinking about the total design problem but only about unconnected fragments.

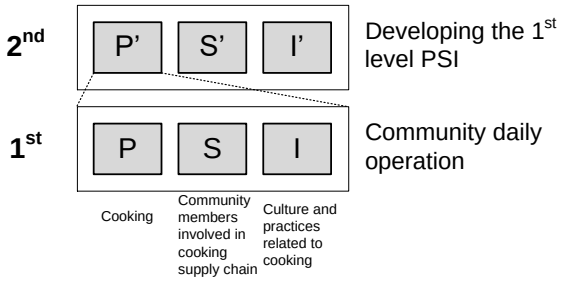


*Figure 2. Modeling the cooking problem with a 2-level PSI framework*

## 5.2 The Cases of Rural Electrification: PSI analysis of a success and a failure

### *5.2.1 Rural Electrification by grid extension*

Another example of failure in development is the case of rural electrification in India. In its quest for modernization of rural villages, India created an ambitious program to electrify about 600 rural villages in 6 years by creating an electric grid to be supplied by large power stations (Harish et al., 2014). This program was to extend electric power distribution lines to villages and if 10 percent of the households in a village were electrified then the village was deemed to be electrified. Even though many villages were connected, the problem of supply was acute leading to the issue of intermittent services that ranged from 2 hours a day to 6 hours a day in different regions of the country. Often the power was not available when needed, in effect making the service useless to its consumers.

In this model, the approach that had been used in developed countries with centralized power generation and distribution networks was being replicated by the government. There were only half-hearted attempts at producing decentralized power. This dominant model of design persisted even though supply often could not keep up with demand and there were poor institutional structures to maintain the infrastructure leading to frequent non-functioning of the distribution systems. While this has worked in urban areas, in rural areas electrification has always been a challenge as it was addressed only technologically. It was shown in the work by Harish et al. (2014) that a combination of extension of the grid and local power generation could overcome the costs of unreliability of the grid. In this model the problem was conceived as grid-based electricity provision by the central government without any concern to the institutional needs and daily needs of the people.

### *5.2.2 PSI in Solar power based Rural Electrification: A success story*

SELCO is a social entrepreneurship that works with solar power for lighting and electrification for the poor in the rural market in India, starting in 1995. SELCO was started as a one-man operation trying to sell solar-powered lamps in Rural South India (Hande, 2010; Mitkowski et al., 2009). The first problem that was faced by Harish Hande, the co-founder, was that people such as street vendors and the poorest were not able to buy the lamp that was 300 to 400 rupees ($4-6US). So, in order to make it easier for them, he came up with a scheme for them to pay 10 rupees a day instead and that made it possible for them to engage as they did not need to have access to cash for purchase. However, this alone was not enough – he had to also make sure the solar power systems' lamps were serviced and maintained, and to do this he picked people who were bicycle mechanics or others with some technical ability (even with minimal education) and trained them. This provided employment and a local servicing capability leading

to increasing adoption. In PSI terms, see Figure 3, Hande, operating at the 2nd level PSI framed the problem in the P' by incorporating knowledge about the whole 1st level PSI; he addressed the problem of lack of skills in the S' space for the product to be sustained by creating an institution in the I' space to address that problem.

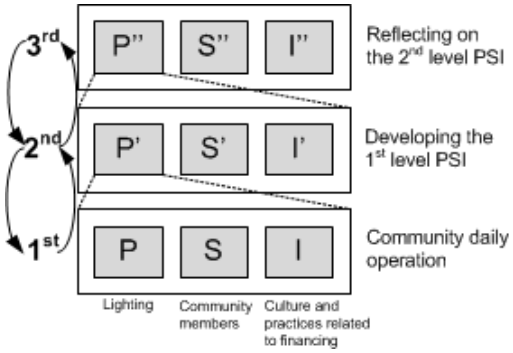


*Figure 3. Modeling the SELCO case with a 2-level PSI framework*

Inspired by the success of the program in its limited reach SELCO decided to scale up the operation using a franchisee model (creating a new I'). However very quickly, the scale up was not achieved and the company was at the verge of bankruptcy due to pressures from the investors. The root cause of the problem was that the franchisees, without any commitment to serve the poor, were not selling it to the poorest but to those at higher income levels where the market was weak. In PSI terms, the problem was a missing 3rd level of reflection as shown in Figure 3. Reflection looks at the lower level and tries to detect and correct misalignments. The franchisee model (I') was misaligned to the original problem definition (P'), but it could not have been detected without the 3rd level. On the verge of collapsing, this level was created.

SELCO realized (P'') that there is need for realignment of the I' to be able to address the original problem of providing the poor with lighting and electric power. SELCO also realized that using off-the-shelf components and creating a standardized model of the product was insufficient to address the varying needs of its customers. This led SELCO to reorganize itself by changing the focus of the product to customer centric products and starting its own regional sales and service centers. The regional centers were supported from the central office in terms of managing accounting, product design and finance. SELCO also created a complex financing and credit structure, identifying investors who were willing to live with lower single digit returns on investment and addressing issues of guarantees for repayment to banks with individuals and organizations who were willing to provide them. Here, SELCO changed the S' space in terms of investors, the I' space in terms of the new structure of operations, to address a new framing of the problem (in P'). Along these lines, SELCO also made arrangements to collaborate with specific NGOs that served the needs of the poor such as the women’s empowerment organization SEWA. SELCO's product had to change and adapt beyond household use of lamps as the needs of the rural customers and their livelihoods and life practices were studied through the project. A modular system was created that allowed flexible use of lights as and where needed. In this entire process, the P' space for SELCO's design changed from a standardized lamp to a modular lamp, to include also financing systems and also repair and maintenance shops. For this shift, the S' space changed from just comprising Hande by himself to include the street vendors to women’s groups to people in varied occupations in designing the product and the financial structure with financial experts and the banks. Subsequently, in working with rural customers, the need for repair and maintenance (skills required at S') and for new institutional structures for training people (I') were identified. In each stage Hande faced obstacles including uncooperative banks who would not give credit to many of his poor customers (I), variable acceptance of the technology (S), the need for assurance of service once bought (I) and the need for easily operated, contextually situated products (P). In dealing with each of these, the design team either had to co-opt existing institutional structures or create new ones to address the growing problem scope (P') and the social dimensions that increase with the scope and concomitantly the institutional structure.

SELCO eventually set up an innovation lab (S' and I') that was directed at new products for the poor that included solar-powered head lamps (P) for rose pickers and silk worm workers. The success of SELCO has come because the company paid attention to the PSI space in spite of the fact that as a company it

grew out of necessity in a developing country with weak institutions. As we have seen in the alternative case of the cook stove, the institutions were too weak to sustain the product and no effort has been made in a systematic way as in the SELCO case (Harish et al., 2013; Hande, 2010). SELCO now is entering the cook stove market.

This and the other example in the text can also be analyzed in terms of how the problem was conceived, by whom and for whom, what were the institutional structures that existed before and what changes are needed to deal with the changed context. From a PSI perspective, the P' space as defined depends on who is involved in defining it (S' space). Mobilizing the right people and skills at the S' space would lead to considering in P' also all issues relevant to the S and I spaces. Once P' is framed in such a holistic manner, each solution will co-evolve the P, S, and I spaces in tandem and aligned. In the case of the cook stove, a first step would be to ask the women about their daily life and practices, a second step to examine the supply chain as most of these new stoves use processed biomass or prefabricated pellets. The need for women to earn money to substitute for their time in collecting free firewood means they will have to have a stake in the production fuel and even the supply (possibly local) of the stoves. For example, in India, women typically spend on average 347 hours a year, collecting firewood (Practical Action, 2015). The problem is not simply the stove; the problem is a complex systems design that includes technology and institutions that needed to be recognized. PSI provides a means to ask the right questions whether in development or design. There are other successful cases that have worked as in the case of SELCO. In those cases, the organizations evolved to address the problem in a holistic manner that involved expanding social space, problem space and institutional space (Brilliant and Brilliant 2007). In all development problems, the original issue is not known and it requires understanding and adapting to the context that includes institutional design.

## 6 DISCUSSION AND CONCLUSIONS

In this paper, we have expanded the relationship between economic development and engineering. We have explored this relationship by characterizing current models of economics-centered development and the role engineering and technology has played in development. We use the PSI framework to extend the scope of engineering design to a holistic view that includes the actors and the institutional structures that are integral to engineering design in context. We use the framework to present two case studies of technology design and introduction in the Indian context to explain failure of the first and success of the second. We concur with Bhalla's (1979) call for 'appropriate technology' - that "application of technology developed elsewhere will not lead to the best results and may even be counter-productive". Our major contribution is the use of an expanded theory of design in the PSI framework to account for failures in engineering technology for developing world context and to provide a framework for the design of that appropriate technology. Viewed with this framework, it is clear which issues need to be incorporated in development projects including their sustainability. It is also clear why previous approaches fail because they do not partner with the necessary stakeholders to create S' that could frame the problem P' with all its richness. Very often, they simply use P'=P. The approach we presented is also of relevance to contemporary societal problems. It is our contention that engineering approaches when extended provide us with the ability to use them in understanding and delivering the needs of the people we serve technically, socially and institutionally.

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## ACKNOWLEDGMENT

Eswaran Subrahmanian was funded by Distinguished Visiting Fellowship DVF1617\5\80 from the Royal Academy of Engineering, UK.

# THE PSI MATRIX – A FRAMEWORK AND A THEORY OF DESIGN

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## Abstract

Real life design situations often involve addressing complex multidisciplinary problems that are hard to formulate and solve, attempted by a diverse group of people, working in different organizations with different cultures, collaborating through a variety of contracts. Many design efforts fail due to incomplete understanding of design contexts. Can we create a framework that will help us unpack this complexity into a structure that allows us to explain, predict, and control failures and improve such situations to help organizations design better? We present a framework, called the PSI matrix that was developed by combining knowledge from diverse disciplines; following numerous case studies with industry to address the above-mentioned challenge. We describe the framework and its evolution from an earlier version, demonstrate its applicability to several diverse design examples, and mention several other cases on which it was tested. We have found it to be robust in supporting its objectives and continue to develop it to improve its added value to design by conducting multi-case, transdisciplinary, multi-context study with numerous partners.

**Keywords**: Design management, Design theory, Organisation of product development, Framework of design

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Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol. 7: Design Theory and Research Methodology, Vancouver, Canada, 21.-25.08.2017.

## 1 INTRODUCTION

Consider the following story, remote from engineering, but nevertheless, a representative of *design* situations. You have a relationship with your spouse; you live your daily life in a way that evolves naturally without thinking about it. Over time, problems surface and communication is not working ideally; you and your spouse do not manage to resolve the differences, (1) in Figure 1a. You consider breaking up the relationship. As a last resort, you decide to approach a professional relationship counselor to help you (2). Your meetings with the counsellor are set outside the daily life situations, through an informal contract that explains how the counselling process will take place (3). In the sessions, after an introductory meeting, the counselor asks the two of you how would you like your relationship to be, what is your fantasy relation or your vision. The counselor may do it at a meeting with both of you or separately, but finally, with the counselor's help, you arrive at a consensus about this vision (4). From thereon, the counsellor will propose a process through which you and your spouse can check the possibility to rearrange your life (5) and decide to continue your relationship according to new agreements (6). If there is no agreement between you and your spouse about the vision of your relationship, the counsellor may propose (7) or any one of you (8) may decide to break the relationship. During the process you may seek another counselor because you do not find a common language with the counselor (9). There could also be different scenarios that this process could unfold.

Consider a different approach to setting up a relationship. After a period of acquaintance, you and your friend decide to formalize your relationship and you sit with friends, family, and other people of your choice to set up your relationship through a contract. You make your vision explicit, (1) in Figure 1b, and following explicit dialogue and agreement, you describe how the daily life would look like including how controversies would be settled in a written document (2). You then continue life according to your agreements (3).

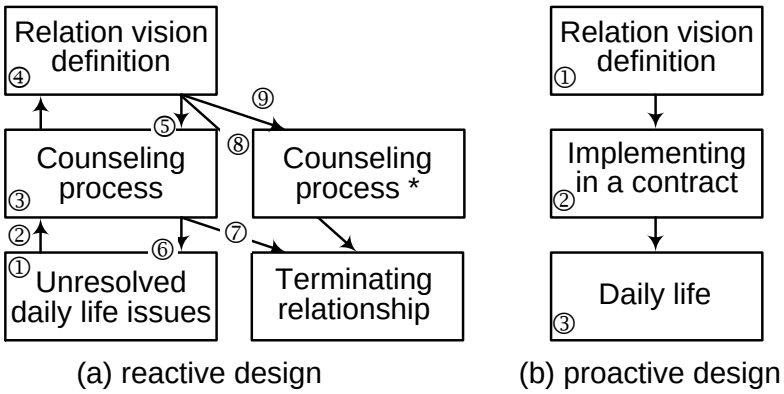


*Figure 1. Couple relationships*

These two stories, the reactive and the proactive approaches to designing (life) are depicted in Figure 1. They are ideal models as in real life, problem definitions and their solutions coevolve (Braha and Reich, 2003) leading to intertwining reactive and proactive processes. You may ask now what do these stories have to do with engineering design or any other type of technology development? We offer two responses. First, we conceive of designing as an information-centric activity. Designing brings together diverse disciplines, making use of different languages, knowledge and models about the world that require dialogue to form shared meaning and mutual agreements. These models evolve and accumulate to a shared body of understanding we call the theory of the artifact (Monarch et al., 1997). Its proper management over time is necessary for a design project to be successful. From this perspective, there is no difference between designing a couple's relationships and dealing with daily life situations to dealing with office situations and developing technical products.

The second response will be apparent as we proceed in this paper; it will become clear that what we have articulated are universal patterns of designing that can be modelled through a framework called the PSI matrix which is composed of PSI spaces (Reich and Subrahmanian, 2015; Meijer et al., 2014). The PSI spaces are a culmination of 30 years of research and development projects aimed at understanding and supporting designers (Subrahmanian et al., 1997).

"The PSI spaces are part of a framework for studying designing as practiced in the real world: framing and solving technical, social or organizational goals embedded in the existing socio-economic and institutional cultures and practices (Reich & Subrahmanian, 2015)." The framework is composed of three spaces, each addressing a key question: P – problem space – addresses the what of designing; S – social space – addresses the who of designing; and I – institutional space – addresses the how of designing.

In the couple story, the P could be daily issues to resolve, the contract, or the vision, depending on the situation; the S could be the couple and other people with whom the couple engages in daily life, the couple and the counselor; the I could be social norms of marriage/relationships, informal culture of the couple's home or the counseling agreement. There need to be some alignment or equilibrium between the spaces for a design activity to be successful. A couple with particular personalities and issues would have to find a suitable counselor to be able to guide them to a safe place.

In the last few years, we have applied PSI on numerous case studies; we were actively involved with some of them and others appeared in the literature. We found PSI to be valuable not only in unpacking a complex situation and understanding it, but also for drawing insight about its future improvement.

Initially, we presented a single-level PSI framework (in the couple story this would be only the daily life situation). Nevertheless, our analysis of other cases made it clear that two levels are necessary. Examples of failures of projects or organizations (e.g., Kodak or Polaroid) and of companies recovering from such situations (e.g., Boeing and the Dreamliner project), led to a 2-levels framework wherein the first level, the usual work is done and at the second level, a reflexive examination and design of the organization and its operation and products is taking place. This work describes the extension to a three or higher level framework which we call the PSI matrix.

This paper describes the initial PSI framework (Sections 2) and its extension to a matrix (Sections 3). Section 4 briefly presents the PSI matrix as a design theory and Section 5 concludes the paper.

## 2 THE PSI SPACES

Designing is a complex activity taking place within a rich context of diverse competing conditions. The PSI spaces is an attempt to understand this complexity by creating a model that will be rich enough to model the scope of designing yet not too complicated to be useful. As designing touches upon all aspects of life, diverse disciplines such as engineering, sociology, psychology, management, and economics, have taken it as an important subject for inquiry. These disciplines use diverse languages, methods, and tools leading to *different* perspectives. By and large, these perspectives are not integrated together and mostly do not converse with each other, leading to a partial and even distorted view of designing that lends credibility to the statistics that most products conceived by designers fail by the time they reach or diffuse into the market. These partial and incomplete views of design also manifest themselves in many failures of systems of all kinds.

Consequently, the first motivation of PSI is to bring together the major aspects in designing into a single model. The PSI integrates the variety of disciplines mentioned above and others. This assemblage of disciplines is set to address three fundamental questions about designing:

*What problem is being addressed*? The problem space – P – requiring knowledge from disciplines including engineering, science, social sciences, R&D, and marketing; these disciplines are required to understand how to assemble knowledge to formulate the problems, and to transform it later into a product;

*Who is included in designing*? The social space – S – requires knowledge from disciplines including sociology and psychology; these disciplines allow understanding how stakeholder personalities and teams makeup determine their interactions and their ability to deal with the complexity of P and I;

*How is designing executed*? The institutional space – I – requiring knowledge from disciplines including economics and management; these disciplines provide the necessary background to understand different institutions cultures, structure and relationships, and the way that context and market impact their operation.

### 2.1 The PSI spaces dimensions

Each of the spaces, P, S and I is further characterized with several dimensions. The dimensions are meant to provide more expressive power to represent the complexity of design situations. In order not to complicate the model too much, we offer 3 dimensions to each space.

**The P space** is characterized with the following dimensions:
*Disciplinary complexity* denotes the number of disciplines and their relationships that are required to understand the problem and design the solution. The notion of disciplinary complexity is important as for each of the disciplines there are models, vocabulary and languages that need to be weaved to design. The more disciplines and more interactions between them are necessary for addressing a problem, the more intricate the process, the theory of the artifact, and the solution are.
*Structural complexity* is the decomposition of the problem into issues and their relationships. As problems involve more issues and as their relationship approaches tight networks rather than hierarchies, the problems become more complex. Managing the information related to their solution becomes an issue of balancing the different knowledge sources, their constraints and contradictions. Without proper capabilities and practices, such management could fail in modes that can be normal, emergent, and unknown (Perrow, 1999). We make here the first connection between the P space, the skills that will be described in the S space and the practices from the I space – these have to match each other for the management of the artifact theory to be successful.
*Knowledge availability* for designing is another important aspect. Available knowledge makes designing easy while knowledge that is presently unknown may be linked to several disciplines leading to gaps that need bridging by later dialogues. This may require complete design situations such as designing R&D projects, experiments, and integration facilities.
We note that complexity arises not only due to more disciplines, parts or missing knowledge but also due to the relationship between the elements. This nature of dimensions appears in all the spaces and dimensions. Also, increasing the complexity in one dimension has a tendency to complicate the others: more components will likely be involved with more disciplines and the chance of missing knowledge for designing some of them will increase.
**The S space** characterizes the social entity that addresses the design problem. This characterization uses three dimensions.
A *perspective* is a "point of view" required to formulate the problem and design the product. Marketing, conceptual design, testing, packaging, and maintenance are all perspective required to design a product to function well throughout its life cycle. Perspectives may interact with each other in complex ways. Due to the division of labor and professional specialization, different people may be needed to present the required perspectives in the design.
*Inclusion* describes who could participate in the design process. Closed social space may keep necessary perspectives outside, leading to failure, but may be easy to manage and keep intellectual property safe. In contrast, open space may complicate the process management leading to failure from a project management perspective but will make access to all knowledge available open. We see here again the tight relation between the S and I spaces.
*Capabilities/Skills* are different notions than perspectives. Skill is an ability to apply different ways of thinking such as creative thinking, critical thinking, and system thinking. A problem that does not require high level of systems thinking and creative thinking is bound to be simpler than one that requires high level of such skills.
As in the P space, a change in one dimension often triggers change in the other dimensions. A need for additional perspectives or skills will probably lead to opening the space to more participants.
**The I space** represents the rules, methods, procedures by which all the participants will be designing the product; it is also characterized by three dimensions.
*Ties* are the connections between actors in the social network addressing the problem; these could be weak or strong (Granovetter, 1983). Weak ties are characterized by the small number of transactions with very low exchange of knowledge and cooperation between the parties. Weak ties are often market-based ties involving low volume of knowledge transfer and dialogue. In contrast, strong ties may involve significant knowledge exchange and reconciliation between different perspectives and disciplines; as such they require careful procedures and commitment to dialogue and sharing.
*Knowledge accessibility* determines who and how different parties involved in the design can access knowledge available in the organization. Obviously limiting knowledge may harm or even fail a design.
*Institutional complexity* reflects the rules, culture, procedures and other formal and informal organizational structures. These could support or hinder the effectiveness of participants. They clearly have to match the nature of the problem being addressed.

## 2.2 The Kodak PSI case

To illustrate the framework, consider the case of Kodak's failure to properly participate in the digital camera market leading to its bankruptcy in 2012, while in fact, Kodak invented the first digital camera back in 1976 (Lloyd and Sasson, 1977). As the new technology had nothing to do with Kodak's film products, and in fact, went against it, management wanted this invention to be kept silent (Deutsch, 2008). Later, Kodak even had a product, Advantix Preview, that allowed users to view their shots digitally and decide which one to print. This product cost more than $500M to launch but was a failure – why would one buy a digital camera if the end result is printing (Carroll and Mui, 2009)? Finally, in 2003 Kodak released their EasyShare family of digital cameras that allowed taking pictures and easily sharing them online (Economist, 2016); Kodak nevertheless, did not foresee the ability to turn this into a "Facebook" type customer experience; it did not understand the social nature of pictures. Kodak had the technology; it was a leader in many technical aspects and first to market; in 2005 it had the largest digital camera market share in the US, yet this reign lasted for a short time only. Kodak in fact, lost money on its cameras. They were developed towards a hi-end market and competed against consumer photography market products. When the digital camera market begun to shrink due to the appearance of cellular phones with cameras, Kodak had no response. Several years later it filed for bankruptcy. Kodak, once among the most valuable brands in the world virtually collapsed while its Japanese rival Fuji succeeded to reinvent itself (Economist, 2016); it took Kodak several additional years to come out of its bankruptcy and become profitable again.

Let us try and use the PSI framework to unpack this story. In the P space, Kodak failed to define the problem properly as history unfolded. It kept the same problem definition of taking pictures without paying attention to the consequences of emerging technologies. Perhaps Kodak was missing some disciplinary knowledge in areas outside technology or perhaps the problem was located in the S and I spaces. From the knowledge perspective of the P space, Kodak was position perfectly with all available knowledge and technology to address all future markets that turned out to be critical. In the S space, Kodak was missing managers with foresight and openness skills, systemic thinking, and change leadership (Barabba, 2011). Observing the technical ingenuity of Kodak’s technical people, these skills were not necessarily missing at Kodak but they did not play a role in determining the fate of the company. Kodak was missing some perspectives also: of the users and their evolution. At times it was focused on women as the majority of the customers and when this changed, they found it hard to respond. The Advantix Preview project suggests it was developed without much customer perspective. The I space had its problems also. For example, trying to hide the first digital camera project, preventing knowledge access, did not help; it may have prevented clever minds in the company to move it forward into the market in a different strategy than the one subsequently adopted. The culture of the company also was harmful. Kodak believed in perfect technology. This opposes the more current culture of consumer products that produces and sells products and then develops better ones by fixing and further development. In addition to managers' inertia, such approach also prevents from quick response to market changes. Kodak monopoly over the market for years made it think it knows the market rather than immersing itself in the trends as they unfolded. The deficiencies in the different PSI spaces, separately, are sufficient to explain Kodak's failure, but there were other clear indications also. Without proper skills and wrong culture, it is impossible to sense the market and define the problem well. Kodak seems to have entered into an unstable company position where missing disciplines or skills cannot be addressed due to incompatible culture or other skills and perspectives.

# 3 THE PSI MATRIX

## 3.1 Extending 1-level to a 2-level PSI framework

In another case, C, a transformer company expanded from a local producer and supplier to a global producer and supplier of the product. To achieve this goal, the company bought several transformer companies in several parts of the world. These companies had their own practices worked out well and their PSIs were aligned in the context of their local markets. C's expansion was predicated on leveraging economies of scale by integrating these different companies. But this required understanding that the new product is different than the collection of the previous products developed separately and is changing the operation of the combined company including sharing knowledge across companies and for that, moving from paper-based mechanisms to computerized support for distributed work. What

exactly had to be done to align the new combined S space with the new P and which I should be created was unclear. The situation at that point was a collection of PSIs waiting to be changed as depicted in Figure 2 in the 1st level.

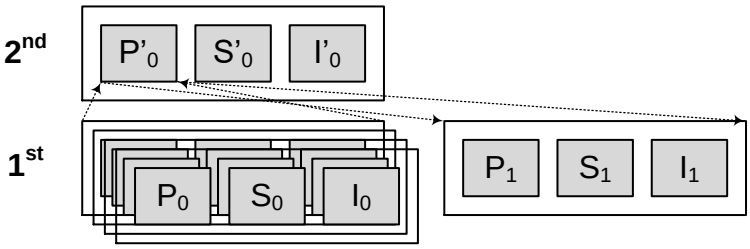


*Figure 2. Two-levels PSI: The move from a local to a global company*

To align the spaces, the company created a team that included people from the different merged companies, such as R&D managers, production managers, and marketing managers. The team also recruited people from the academia, including us, thereby created a well-rounded $S_0'$ space. The mode of operation of this team, its $I_0'$ space, was subject to the company procedures and contracts made with the external participants. The problem given to the team, its $P_0'$ space, was to align the PSIs of the organization; this is depicted with the dotted arrows from the PSI at the 1st level to the $P_0'$ at the 2nd level PSI.

The team created a new shared product structure model, including computer-aided tools that modeled the physics of the transformer using collective empirical data from the acquired companies. A new design environment was created that captured the shared memory as the design progressed. The end result of this team work was a new and aligned PSI $[P_1, S_1, I_1]$ shown in Figure 2.

Consider another case of a company growing from a startup developing a new vision sensor, to transform into a multinational company involved in developing devices for control of autonomous cars (e.g., Mobileye could be such example). Clearly the initial narrow problem and corresponding product that was designed and the design team and its practices are very different from the set of devices and clients, the multinational team, and its institutional rules and culture. The practices of the large company will not work in the startup and those of the startup will fail the large company. There needs to be alignment in the PSI spaces. How could we conceive of the process of company growth through aligned spaces? The answer could be by moving through intermediate stages in which alignment is achieved, after every change, through some design activity. For that design activity, the problem to be addressed is the misalignment in the PSI spaces. As in the case of company C, we need a 2nd level PSI whose task is designing the solution to intermediate misalignments in the organization's PSI. Figure 3 shows such company evolution. The 1st level PSI, $[P_0, S_0, I_0]$, shows the first time the company needed to grow, perhaps when receiving the initial pre-seed funding. A team, probably very small, or even only the investor, $S_0'$ at the 2nd level, determines the new focus of the product, whether new people have to be recruited, and the mode of operation, leading to a new $[P_1, S_1, I_1]$ at the 1st level. When the next major development occurred, a new PSI is formed at the 2nd level $[P_1', S_1', I_1']$ to align the spaces again leading to a new PSI at the 1st level and so forth until the $[P_{n-1}', S_{n-1}', I_{n-1}']$ PSI at the 2nd level created the last PSI at the 1st level, $[P_n, S_n, I_n]$.

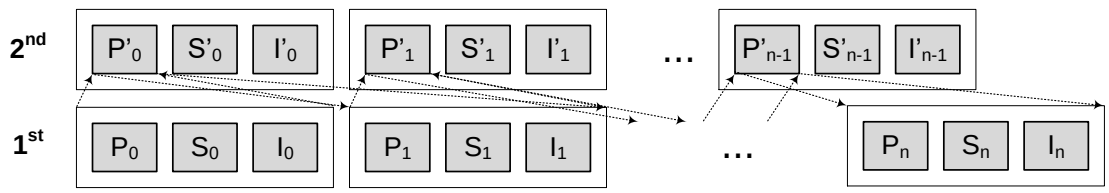


*Figure 3. Two-levels PSI: the move from a startup to a multinational company*

We anticipate that the team and its practices at the 2nd level would not need to evolve often compared to the pace at the 1st level. We also contend that once formed, the 2nd level team could redesign itself if necessary to address new PSI alignment challenges. The reason is that the team at the 2nd level has skills and knowledge to perform alignment and could use these resources in a reflective mode to correct

itself. Since each issue that arises can be dealt with by invoking PSI, the team at the 2nd level is actually also reflexive (Reich, 2017).
The two last cases demonstrate that a change in a PSI characterization, whether proactive or reactive requires a second level PSI where the move towards alignment is being designed. At that level, the whole 1st level PSI becomes the problem and the *S*' and *I*' spaces are designed to allow addressing it.

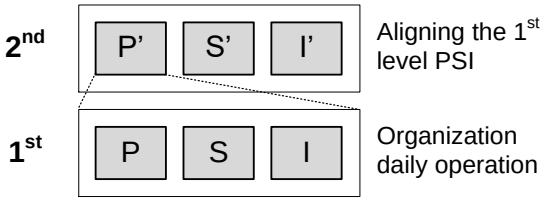


*Figure 4. Two-levels PSI: the 1st level describes the daily work of the organization while the 2nd level aligns the 1st level PSI*

### 3.2 Moving to the 3rd PSI level

Going back to the case of C, it is clear that the whole move from local to global was based on significant deliberation at the company and a final decision to adopt this move. We may call this decision a new vision of the company that was a result of addressing some need or desire to grow and increase value, all of which could be considered to be part of some *P*" space; addressed by some team, company major shareholders, the CEO and others key stakeholders, forming the *S*" space; through some process, represented as the *I*" space. Where would we position this vision definition activity? We contend elsewhere (Reich et al, 2017) that vision, ethos, or the meaning of an organization or community is a product that requires its own level; this level is the most abstract PSI level. The case of C makes it easy to defend this view. The process at this company was proactive therefore successful (although it is not always like that). The conclusion of the 3rd level PSI with a new globalization vision for the company, led to forming a different team, *S*', at the 2nd level PSI that planned the integration of the acquired companies into the mother company, leading to a new PSI at the 1st level as already described in Figure 2. This overall process is shown in Figure 5.

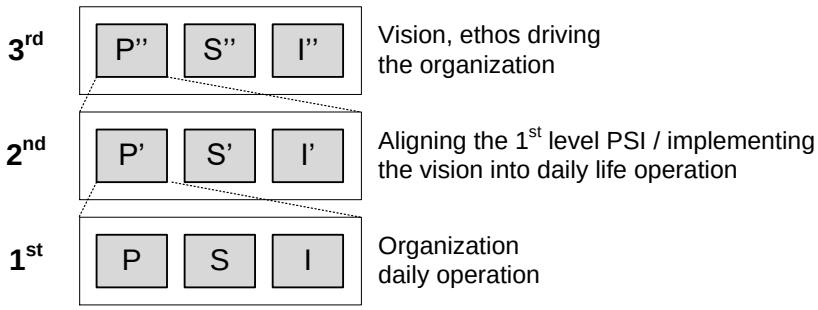


*Figure 5. Three-levels PSI: from vision to working company in a proactive process*

We clearly see the similarities between the story of company C and the couple story in the introduction and consequently the similarity between Figure 1 levels and Figure 5 levels. Figure 5 now becomes the PSI matrix which is a model of our design framework. Why is it a model? because it does not display all the possible interactions between the spaces in the different levels. For example, although we have three separate S-space cells in the matrix, *S*, *S*', and *S*", it is clear that there are people, such as the CEO, whose perspectives are represented in all three S spaces. We can attempt to draw the PSI spaces as a complex network of relations to be more precise. The choice of model boils down to level of understanding, ease of use, and functionality of the model.

### 3.3 Working with the 3 levels

The PSI matrix carries the properties of a single-level PSI framework – all spaces need to be aligned. For the levels, we need that they be synchronized for the organization to function properly. We use synchronization and not alignment because alignment is a property that is maintained at the same time in the spaces while synchronization allows for significant time delay as we see later. A company that

develops products that sell in the market but that do not correspond to the company values and vision will not last long. All levels have to be synchronized. The case of C where a new vision, mission statement and strategy was developed at the 3rd level, that drove the process of aligning the organization at the 2nd level, so that it could improve its performance at the 1st level, is only one simple example of aligning and synchronizing. But there could be many ways in which the PSI matrix is put to work. We achieve the alignment and synchronization by thinking about designing from an information management perspective.

In numerous studies we accumulated experience in actively participating at the 2nd level PSI to help organizations align themselves to their vision and to their market needs (Davis et al., 2001; Sitton and Reich, 2016; Subrahmanian et al., 2015). These alignment processes included detailed analysis of the organization vision and its derived core processes; information flow studies to identify stakeholders, bottlenecks, and responsibilities for these processes; and defining support infrastructure to allow smooth information access and sharing. In some cases, the 2nd level PSI was operated as a project to get the organization on track and in others, a new department was formed in the organization to continually monitor the health of the day-to-day operations thus giving permanent shape to this level by building expertise, skills, and knowledge inside the organization and fixing the *I'* space as the charter given to the people involved in the *S'* space of this level. Details of these studies appear elsewhere; here we only illustrate intuitively how our experience in these projects translates to knowledge for aligning and synchronizing the PSI matrix.

Let us start with a healthy organization where all its 3 levels are aligned within and synchronized across. Reality changes all the time, often accompanied by challenges. The first task is to detect existing misalignment or lack of synchronization. From an information management perspective, any issue that arises in the smooth flow of relevant information on time to whoever needs it in the organization may be a sign of a problem. It could mean rules that prevent access of information in the I space, missing perspective that is detected in the process (S space), gaps in knowledge (P space), failure of a product due to lack of openness to customers (S space), weak ties between company and suppliers leaving critical information outside the transaction, or procedures demanding a long authorization of decision that hampers quick response (both in the I space). These problems could be detected and their sources identified. Each fix may mean a change in a space leading to cascading events. Such changes at the 1st level have to be reflected upon at the 2nd and 1st levels. The task of the 2nd level would be to make sure that cascading events do not occur without careful path evaluation and plan adaptation.

Let us try to explain how this multilevel synchronization works through a mechanical metaphor. Consider that each space in each level is represented by a spring, red for P, blue for S and green for I as shown in Figure 6. At each level, these different springs have different properties and therefore different stiffness. When a vision is developed for an organization, it looks like stretching the springs to the right direction. The springs have to be in equilibrium to be stretched together even if not stretched by the same amount. The influence of this layer on the lower level is through some friction layer. Some of the energy from the top stretch dissipates but some is passed to the implementation layer. Again, its spaces are stretched depending on their flexibilities; some are easier to change and some are less. The same process continues for stretching the 1st level. In order for an organization to develop a product P (modeled as the red spring at the lower left), all the system has to be stretched in a particular manner and all the system has to be in relatively stable equilibrium.

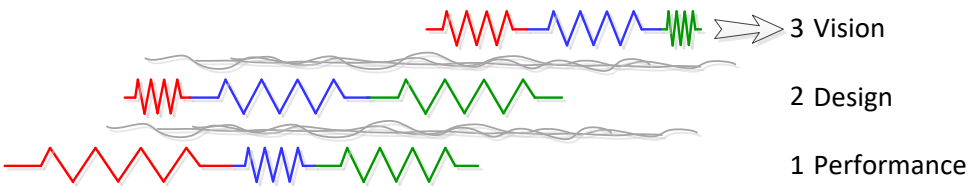


*Figure 6. Aligning 3 levels*

We can use this metaphor to penetrate much more into the PSI matrix. For example, the friction layer between levels makes sure that the top level is only an approximation of what is going on at the lower level. Also, if the springs at the same level are not connected well to each other they might not be aligned and significant effort or resources might get lost in the process.

### 3.4 Examples

We can revisit the Kodak case and enrich the description into 3 levels. At the top level we could discuss the company vision, being a photography end-to-end solution with the slogan: "You press the button, we do the rest." Taken seriously, the central activity was not the camera but the film and its processing to photos which Kodak led. It meant creating an elaborate vertical integration that provided films and got them and processed them effectively. The digital camera was going to eliminate this part but Kodak came up with the EasyShare feature in its cameras. This however did not capture the market. There were other alternatives and the consumers wanted more than a click and pictures. Pictures became a social interaction anchor, but Kodak stuck to its original role and vision by further improving its digital cameras and also moving more into digital printing. The skills we previously described as missing in the S space (foresight, openness, systemic thinking, and change leadership) could now be associated with the 3rd level - S". Kodak leaders were unable to change the vision at the 3rd level.

In the digital era, the elaborate vertical integration of Kodak to "do the rest," was not needed to enter and compete in the market; it became a burden. Using the springs metaphor, the springs were not connected well at the 1st level. Kodak missed changing its vision at the 3rd PSI level; and therefore, it had done little at the 2nd level, only exercising reactive response to the market, and mainly laying off people to address the downsizing felt needed in the social space.

A sample of other examples of using the PSI matrix to explain designing situations include: (1) The metro station in La Défense, Paris (Reich et al., 2017); (2) Resident market design in economics; (3) The design driven innovation approach (Verganti, 2013); and (4) Enterprise systems engineering of an organization and a collection of organizations (Sitton and Reich, 2016). The diversity and details of these cases provide evidence of the validity of the PSI matrix as a framework for designing; unfortunately, their description is beyond the scope and space limits of this paper.

## 4 THE PSI MATRIX AS A DESIGN THEORY

The PSI matrix is not only a framework for understanding designing; it is also a design theory. We only introduce the topic here for lack of space. The role of a theory is to explain what has been observed in designing. PSI has taken a broader scope of explanation in examining the causes or success of designed artifacts. Within this perspective, PSI allows for explaining failures and successes in designing, predict them, and even could potentially be used to control and change the fate of designing situations. For example, we predict that misalignments in a PSI will lead to failure and could even set up experiments to test this. Hence, the PSI matrix has all the ingredients of a theory of design.

The PSI matrix does not claim to explain all of designing, e.g., it does not explicitly explain creativity; we do not believe in a single unified theory of designing. However, the PSI matrix allows us to create contextualized collection of local theories of designing artifacts while providing a framework to understand patterns of failures and successes in their design. This approach is similar to the one taken by Ostrom and her colleagues in their work on understanding institutional rules for managing common pool resources (Ostrom, 2009) to accommodate the variety observed in practice. The PSI matrix can be combined together with, and complement other, theories and it will be also subject to testing, scrutiny and elaborations. Let us take as an example the C-K theory (Hatchuel and Weil, 2009) or the KCP method derived from it (Hatchuel et al, 2009). Previous theoretical analysis using C-K determines that KCP addresses four dimensions of collective creativity "but in a very specific way (Hatchuel et al, 2009)." PSI can be used to explain and perhaps improve the KCP workshop structure and enable it to generalize to different situations. Also, since C-K or KCP may not work in all companies due to their culture or other contingent factors, the PSI matrix could be used to understand this and address remedies for such conditions.

## 5 DISCUSSION

We presented the PSI matrix, as a design framework and theory resting on significant work with industry and design research. The PSI matrix draws knowledge from diverse disciplines to be able to explain the complexity in real design situations dealing with diverse people in multiple teams working in organizations with diverse relations to develop products in diverse ecosystems. We briefly demonstrated in several cases and noted other cases on which it was tested. Nevertheless, the PSI matrix is in its early stages of development. While we see that the matrix as presented here is already valuable, we intend to

improve it further by collecting many cases and studying them to understand the influences between the different spaces (cells) in the matrix as well as their specific characteristics. We are presently conducting multi-case, transdisciplinary, multi-context studies with numerous partners to provide more insight on the utility of the PSI matrix as guidance for design and also to test it as a theory of designing. While they are too early to report, we clearly see the benefit of constantly looking at the situation and its PSI matrix model and deriving guidance for the project. It is clear that many fundamental topics will arise in that process and new research questions be formulated. Dealing with designing in its full complexity requires such a study which is multi-layered but at the same time illuminating and fascinating.

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**Jacquelyn NAGEL**

Jacquelyn K. Nagel is an Associate Professor and Assistant Department Head in the Department of Engineering at James Madison University. Dr. Nagel's engineering experience in both in academia and industry includes: bio-inspired design, sensor design, instrumentation and control, and manufacturing system automation. In 2012, Dr. Nagel was recognized by the National eWeek Foundation and IEEE-USA as one of the New Faces of Engineering for her pioneering work in bio-inspired design. She earned her Ph.D. in Mechanical Engineering from Oregon State University, and her M.S. and B.S. in Manufacturing Engineering and Electrical Engineering, respectively, from the Missouri University of Science & Technology. Dr. Nagel's long-term goal is to drive engineering innovation by applying her multidisciplinary engineering expertise to design, sensing, and manufacturing challenges. Her research interests include biomimicry, design theory, sensors, and advanced manufacturing.

**Title of the Presentation:**

Biomimetics with Design Theory

**Synopsis:**

This advanced course will cover how design theory is being used to formalize the process of biomimicry, or, as engineers like to call it, bio-inspired design. Issues and limitations of biomimicry will be presented to provide the background knowledge of why this research is needed. Approaches to biomimicry using design theory, with emphasis on Concept-Knowledge Theory, will be discussed. The course will conclude with implications for future research and education.

**Main References/ Further readings:**

Nagel, J.K.S., Pittman, P., Knaster, W., Tafoya, E., Pidaparti, R., Rose, C. (2019) "Preliminary findings from a comparative study of two bio-inspired design methods in a second-year engineering curriculum." Proceedings of the 2019 ASEE Annual Conference and Exposition, Tampa, FL.

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For a full list of (and free access to) my papers on biomimicry and function-based design theory, please go to https://www.researchgate.net/profile/Jacquelyn_Nagel

# Preliminary Findings From a Comparative Study of Two Bio-inspired Design Methods in a Second-year Engineering Curriculum

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Dr. Jacquelyn K. Nagel is the Assistant Department Head and Associate Professor in the Department of Engineering at James Madison University. She has eight years of diversified engineering design experience, both in academia and industry, and has experienced engineering design in a range of contexts, including product design, bio-inspired design, electrical and control system design, manufacturing system design, and design for the factory floor. Dr. Nagel earned her Ph.D. in mechanical engineering from Oregon State University and her M.S. and B.S. in manufacturing engineering and electrical engineering, respectively, from the Missouri University of Science and Technology.

**Prof. Christopher Stewart Rose, James Madison University**

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**Miss Peyton Leigh Pittman**
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Wade Knaster is a senior engineering student at James Madison University. In his third year of study he began his research on teaching methods of bio-inspired design under the direction of Dr. Jacquelyn Nagel. When Wade is not studying or conducting research, he finds himself at the University Recreation Center as the Trips Logistical Manager for the Adventure Program. Wade plans to utilize his degree in the civil engineering field designing and analyzing America's infrastructure.

# Preliminary findings from a comparative study of two bio-inspired design methods in a second-year engineering curriculum


## Abstract

The engineer of 2020 is expected to not only offer technical ingenuity but also adapt to a continuously evolving environment while being able to operate outside the narrow limits of one discipline and be ethically grounded in solving the complex problems of the future. To build the competencies of the future engineer, undergraduate education must train students to not only solve engineering challenges that transcend disciplinary boundaries, but also communicate, transfer knowledge, and collaborate across technical and non-technical boundaries. One approach to train engineers in these competencies is teaching biomimicry or bio-inspired design in an engineering curriculum.

Our research addresses the gap in resources for effectively teaching engineering students how to perform bio-inspired design by creating instructional resources based on Concept-Knowledge (C-K) design theory. C-K theory is known for integrating multiple domains of information and facilitating innovation through connection building. We used this theory to create lectures, in-class activities, assignments, rubrics and templates that scaffold the discovery and knowledge transfer processes involved in using natural designs to inspire engineering solutions.

To assess the learning impact of our C-K theory instructional resources, we conducted a statistical comparison of student projects produced in a second-year engineering class exercise using instructional resources from C-K design theory and from the popular Biomimicry Institute (BI) design lens approach. A total of 105 students consented to participate; 2 course sections (N=51) used the C-K approach and 3 course sections (N=54) used the BI approach. Scores assigned to the students' concepts were used to test whether the C-K approach resulted in higher quality design concepts. The sections using the C-K approach were found to generate concepts that more closely resembled biological inspiration, meaning that they demonstrated innovating from nature rather than simply copying from nature. They were also more successful in abstracting biological system principles to create high quality concepts. Sections using the BI approach generated concepts that more closely resembled biological imitation, meaning that they tended to fixate on observable features and produced concepts that look or act exactly like the biological systems. These findings provide conclusive evidence of learning impact and support design theory based bio-inspired design pedagogy.


## 1. Introduction

It is well known that engineering involves integrating broad knowledge towards some purpose, generally to address a need or solve a problem. As we move into a global future, engineers can no longer isolate themselves and must be prepared to work across disciplinary, cultural, political, and economic boundaries. Every day, engineers are confronted with complex challenges that range from personal to municipal to national needs [1]. The ability for future engineers to work

in multidisciplinary, interdisciplinary, and transdisciplinary environments will be an essential competency [2]. Furthermore, with greater emphasis being placed on understanding the social, economic and environmental impacts of engineered solutions, another essential competency is the cognitive flexibility to think about the whole system at different levels of fidelity and in different time scales [3, 4]. Undergraduate education must train students to not only solve engineering challenges that transcend disciplinary boundaries, but also communicate, transfer knowledge, and collaborate across technical and non-technical boundaries. One approach to achieving this goal is teaching biomimicry or bio-inspired design in an engineering curriculum [5]. Bio-inspired design encourages learning from nature to generate innovative designs for man-made technical challenges that are more economic, efficient and sustainable than ones conceived entirely from first principles [6].

Incorporating all STEM disciplines into complex engineering problems will create a new context for undergraduate students to apply knowledge that they already have. Most students that go into engineering have high school level training in biology. Adding biomimicry into the engineering curriculum encourages students to utilize and build off their prior knowledge, which fosters making connections and recognizing interrelationships across STEM disciplines [7, 8]. Moreover, requiring knowledge transfer across domains as well as organizing that knowledge into logical constructs helps to develop future flexibility and adaptive expertise that will facilitate innovation and efficiency [9, 10]. Having to retrieve and transfer knowledge from domains outside of engineering forces students to adapt to unfamiliar languages and content formats (which addresses non-technical skills) in order to apply the biological information intelligently to engineering problems (which addresses technical skills). Additionally, biomimicry touches on many areas of engineering including electrical, mechanical, materials, biomedical, chemical, manufacturing and systems, which makes it applicable in a wide range of engineering programs, from discipline-specific to general ones.

Showing engineering students the significance and utility of bio-inspired design is easy. Teaching them how to do bio-inspired design without also requiring them to be fully trained as biologists is much more difficult. Teaching bio-inspired design in an engineering curriculum relies on either the ad hoc application of biological inspiration or research methods and tools that are tied to specific engineering design methodologies. Typically within the classroom, a tool or method is presented with an example that illustrates the technique and students are expected to practice the inherent knowledge transfer steps required to understand the underlying principle. Much less is known about how to effectively guide students in the knowledge transfer steps that are so crucial to moving between the engineering design space and the biology space. Students are set up to make the creative leap across these spaces, but are not supported in the actual leap. Thus, analogy use/misuse, mapping, and transfer are repeatedly cited as the major challenges with teaching bio-inspired design to engineers [11-19]. This is an important gap to address since effective navigation between the engineering design and biology spaces builds connections that facilitate innovative design and increase engineering students' cognitive flexibility, creativity, and adaptive problem solving skills [20]. The research presented in this paper aims to address this gap through developing effective instructional resources grounded in C-K Theory that will

assist engineering students in transferring knowledge between the domains of engineering and biology.

## 2. Background

This section reviews current efforts to incorporate biomimicry in engineering curricula, as well as the two teaching approaches compared in this study: C-K approach and the BI approach.

### 2.1 Current Status of Bio-inspired Design in Engineering Programs

In response to the increased emphasis on cross-disciplinary thinking skills and adaptive and sustainable designs by professional societies, industry and today's global marketplace, engineering colleges in the United States and abroad are increasingly expanding the scope and focus of their curricula to include bio-inspired design topics and projects that expand systems thinking skills, and has been integrated at the module, project, or course levels [7, 8, 11, 14-16, 18-27]. While instruction in bio-inspired design is quite common in engineering programs at the graduate level, it is exciting to note that bio-inspired design instruction is also being incorporated into curricula at the undergraduate level.

Multiple institutions offer semester long engineering courses in bio-inspired design or interdisciplinary courses that bring together students from STEM and art. Probably the most well known institution is Georgia Tech, which offers multiple courses and a certificate through the Center for Bio-inspired Design [28-30]. The undergraduate interdisciplinary course is co-taught by faculty from biology and engineering, and admits junior and senior level students from all fields of engineering and biology. Two processes for bio-inspired design, problem-driven and solution-driven, are taught in the course, and analogies are formed through functional decomposition similarly to functional modeling in engineering design [29]. More recently, the four-box method that identifies function, operating environment, constraints, and performance criteria as dimensions for matching biological analogues with the design problem has been implemented [31]. Students work in interdisciplinary teams on assignments and projects throughout the course. Honors-level undergraduate courses similar to the one at Georgia Tech have been offered at institutions such as Virginia Tech.

The mechanical engineering department at Montana State University offers a senior level technical elective on bio-inspired engineering [14]. The course covers relevant bio-inspired design and engineering design processes with a focus on structures and materials from both nature and engineering. The practices taught in the course include reverse engineering and tabulating a variety of relationships. Thus, the focus is more on comparison than innovation. Texas A&M is currently developing an undergraduate course to introduce interdisciplinary engineering students to multiple methods of bio-inspired design [25]. The course will be an elective in the mechanical engineering curriculum that focuses on breath of approach rather than depth, exposing students to the state-of-the-art in bio-inspired design research tools and methods. At the Olin College of Engineering, all students take a course that introduces bio-inspired design

in their first semester. The course is called Design Nature and is an introduction to the engineering design process that also weaves in concepts from nature. Students complete individual and team projects in the course. Similarly, all first-year engineering students at the University of Calgary are introduced to biomimicry in their design and communication course.

At Kettering University, in the Industrial and Manufacturing Department, biomimicry is integrated into an ergonomics course through problem-based learning [23]. Students work individually on projects using the Biomimicry Innovation Tool, which blends aspects of problem based learning, innovation, biomimicry, and ergonomics into a single student experience. They present their bio-inspired concept at the end of the course. The University of Maryland offers a course in biomimetic robotics as a senior elective in the mechanical engineering program [19]. Students study biological locomotion and how it can inspire efficient mechanisms of motion.

Bio-inspired design concepts and examples have been used by several institutions to educate students on design innovation and as another source of design inspiration. These include Oregon State University, University of Georgia, James Madison University, Purdue University, Clemson University, Penn State University-Erie, University of Maryland, Indian Institute of Science, University of Toronto and Ecole Centrale Paris to name a few. Often the instruction is across less than four lectures, which reduces the burden of integration into existing courses. These institutions also require engineering students to complete assignments or a project involving bio-inspired design to practice the technique and demonstrate its value. Integration occurs at the freshman through senior levels, in a variety of departments, and depends primarily on when engineering design is offered in the curriculum. Consequently, varying levels of instruction and support are provided to the students, and many rely on the resources provided by the Biomimicry Institute, such as the database AskNature.org. This points to a general lack of engineering-focused, evidence-based instructional resources available to faculty that wish to integrate bio-inspired design into their courses.

### 2.2 C-K Theory

C-K theory, introduced by Hatchuel and Weil [32-34], integrates creative thinking and innovation by utilizing two spaces (Fig. 1): (1) The knowledge space (K) – a space containing propositions that have a logical status (i.e., are determined); and (2) The concepts space (C) – a space containing concepts that are propositions that have no logical status (i.e., are undetermined) in the *K* space [32-36]. This means that when a concept is formulated, it is impossible to prove that it is a proposition in the *K* space. Rather, concepts generate questions and research to answer those questions will generate new knowledge that will provide new attributes for new concepts. The wider the initial knowledge space is, the higher the number of feasible concepts. However, the final result of the concept generation process is initially unknown. The design path is defined as the cognitive processes of generating concepts from existing concepts and transforming concepts into knowledge. Although specific tools are not embedded, C-K theory has shown to reduce fixation and improve the knowledge and creativity of the user [32-36].

There are four operations allowed: expansion of each space ($C \rightarrow C$, $K \rightarrow K$), conjunction which is testing a concept proposition to lead to new knowledge ($C \rightarrow K$), and disjunction which is a new concept being generated from existing knowledge ($K \rightarrow C$). Concepts can be partitioned or included, but not searched or explored in the *C* space. Adding new properties to a concept results in the concept being partitioned into sets or subsets of concepts. The reverse, subtracting properties from a concept, results in subsets being included in the parent set. After partitioning or inclusion, concepts still remain as concepts ($C \rightarrow C$), but they can also lead to the creation of new propositions in the *K* space ($C \rightarrow K$). The combination of different pieces of knowledge and the addition of new discoveries expand the *K* space ($K \rightarrow K$) and can result in new concepts ($K \rightarrow C$). Innovation is the direct result of the two operations that move between the spaces by using the addition of new and existing concepts to expand knowledge, and using knowledge to expand concepts. C-K theory thus provides a framework for a designer to navigate the unknown, to build and test connections between the *K* and *C* spaces, and to converge on a solution grounded in theory combined with new knowledge.

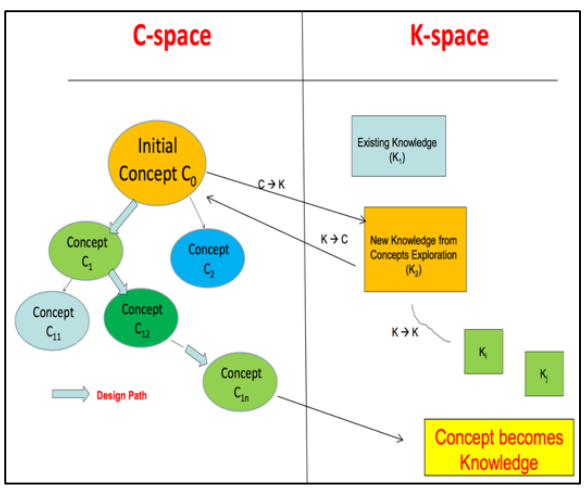



Figure 1: Concept-Knowledge Theory Framework

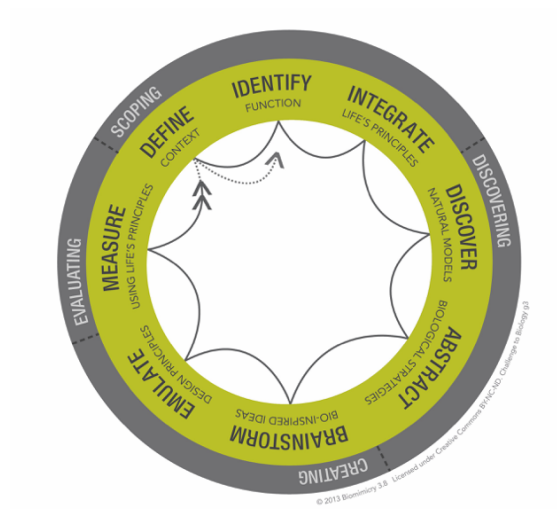



Figure 2: Biomimicry Institute Design Lens

### 2.3 Biomimicry Institute Approach

A popular approach to bio-inspired design is the Biomimicry Design Lens (Fig. 2) created by the Biomimicry Institute. Its popularity is attributed to its accessibility via the Biomimicry Institute's website and to its approach not being limited to a specific type of problem or practitioner (e.g., biologist, engineer). This approach is coupled with the AskNature.org website, which is a public database of biological information organized by a biomimicry taxonomy [37].

The cognitive process of this approach is divided into the steps of scoping, discovering, creating, and evaluating (Fig. 2), and is structured around the search for particular biological insights to

solve a given problem. Scoping involves specifying the problem to be solved with operating conditions, the functions that must be performed, and which life's principles the design will incorporate. Discovering involves identifying biological systems that have evolved strategies to solve the defined function(s) followed by abstracting those strategies into possible design principles. This step is often guided by the question, "How would nature tackle or accomplish the same problem?" Creating involves brainstorming ideas for how to apply the abstracted design principles followed by generating concepts that take into consideration aspects of scale, form, process and ecosystem. The final step of evaluating entails using life's principles as an assessment checklist. As shown by the arrows on the inside of the circle, the process is meant to be iterative to improve the outcome.

## 3. Using C-K theory for Designing Instructional Resources

This section reviews how and why the C-K approach should be utilized to generate instructional resources that integrate biology, engineering, and design theory to establish a two-way connection between engineering and biology, and scaffold the process of discovery for novice engineering designers. As shown in Fig. 3, the cognitive steps involved in bio-inspired design are generally similar to the early phases of the traditional engineering design process. Using a problem-driven approach, meaning the bio-inspired design process starts with a given problem, the problem is first understood and defined. To assist with translating the problem into a context amenable to bio-inspired design, the problem is reframed through abstraction. This generalizes the problem to broaden the inputs for the search task. The third step is to identify biological inspiration sources using a search technique or database. Once a set of inspiring biological organisms or phenomena are identified, they can be studied further to facilitate knowledge transfer. Analysis of biological principles or strategies leads to a deeper understanding of the inspiration sources which can then result in abstractions for analogy mapping. The final step is to generate concepts and select those that can be moved forward to the embodiment phase of the traditional engineering design process. It is in the feedback loop of transfer and apply–investigating a biological inspiration source and applying the learned knowledge by generating new concepts–that the discovery of innovative bio-inspired solutions occurs. During the discovery part of the process, knowledge and concepts are being both used and exchanged in much the same way as the C-K design theory predicts. C-K theory further presents a theoretical basis for formalizing instructional resources that will more effectively bridge the knowledge gap between engineering and biology, and facilitate the discovery of biomimetic innovations.

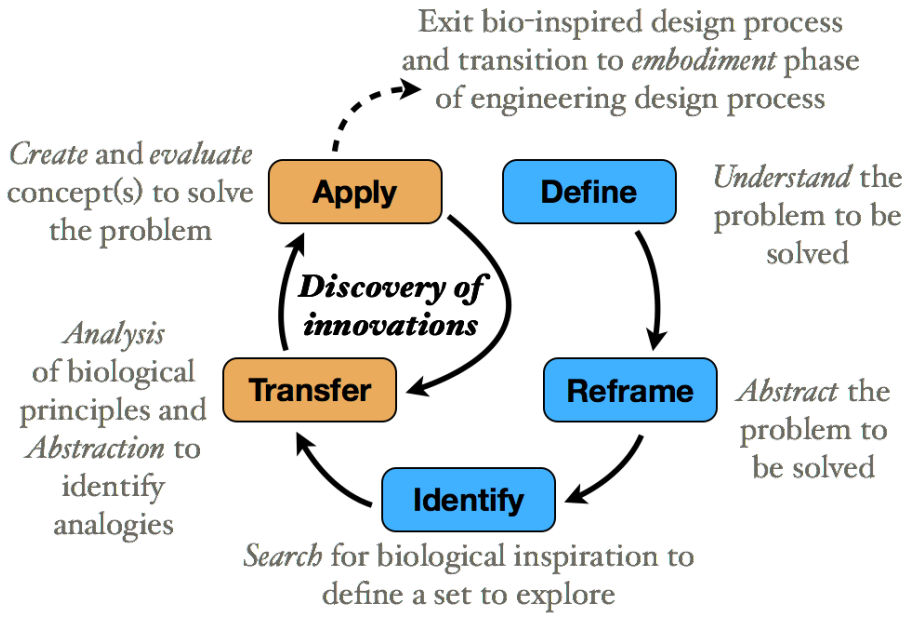


Figure 3: Bio-inspired Design Process

This approach is predicted to offer many benefits. C-K theory is adaptive and generalizable across scientific domains, which makes it applicable to a wide range of engineering problems (i.e., electrical, mechanical, material, chemical). C-K theory also emphasizes connection building through exploration and expansion of the *C* and *K* spaces to iterate to a better solution. Knowledge is therefore not restricted to being a solution space, but rather is leveraged to improve understanding of the innovative designs. Furthermore, C-K theory requires explicit documentation of the design path, thus inherently modeling cross-domain linkages. Table 1 summarizes the characteristics of the C and K spaces that facilitate the discovery of bio-inspired innovations.

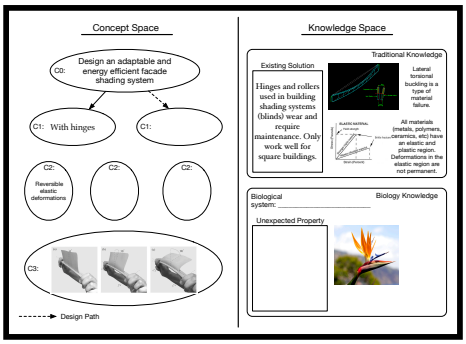
Table 1: Characteristics of the concept and knowledge spaces that support the knowledge transfer needs of bio-inspired design

| Concept Space | Knowledge Space |
|---|---|
| Posing questions to explore/answer | Analysis of existing knowledge (digging deeper) |
| Creation and partitioning of ideas | Drawing connections/linkages across knowledge |
| Documentation of a design path | Recognizing unexpected properties (opportunities) |
| Supports a problem-driven approach | Supports a biology-driven approach |

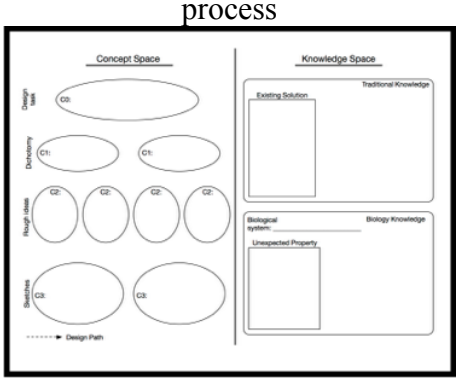
Knowledge transfer from biology to engineering is recognized in the literature as a persistent challenge for bio-inspired design [38, 39]. Specifically, the understanding and evaluation of biological models, the abstraction of biological principles or strategies, and analogy mapping all need to be addressed to make bio-inspired design a widely adopted process. Salgueiredo [40, 41]

first proposed applying C-K theory to bio-inspired design, and provided a starting point for developing our C-K theory based instructional resources shown in Figure 4 [42, 43].


Teaching Module: exposure to breadth of inspiration and innovation and models the process




Learning Activities: In-class exercises that promote active learning and development of cross-domain linkages




C-K Mapping Template: visually structures the knowledge transfer process

Task 1: Use C-K map to create a solution for a sub-system of the course design project system

Task 2: Develop a full system concept incorporating the inspiration

Task 3: Answer reflection questions for the process and content - 'What did I learn?', 'How did I learn it?' and 'What will I do with it?'

Assignment: practice developing cross-domain linkages and reflection

Figure 4: C-K Theory-based Instructional Resources

## 4. Background for the Comparative Study

Our comparative study to test whether the C-K theory instructional approach improves the quality of bio-inspired design concepts was carried out on second-year engineering students in an engineering design course at James Madison University. These students are in the first semester of the engineering design sequence of the curriculum and are learning the engineering design process while applying the tools and methods to a course project. A total of 105 students in five sections of the course consented to participate in the study. 51 students across 2 sections were instructed to use the C-K approach and 54 students across 3 sections the BI approach. All students first received a lecture on bio-inspired design in a single 100 minute class period. The lecture had three parts: (1) design by analogy, (2) fundamentals of bio-inspired design with key examples, and (3) presentation of one of the two instructional approaches with in-class learning activities. Each student was then asked to complete an assignment using the instructional approach they had been taught, and submit it the following week.

The lecture began with the fundamentals and key examples of bio-inspired design, starting with analogy. For our purposes, analogy means using similarities between two entities that are otherwise dissimilar for the purpose of explanation or clarification. Students are presumed to have enough familiarity with one of the entities that its comparison with the other helps to draw connections to the latter. For example, electrons rotating around the nucleus (a high school- or university-level cognitive challenge) can be compared with planets rotating around the Earth, which is a middle school concept and one that most students are comfortable with by university age. Students started thinking about analogies by doing an in-class exercise of developing a concept for an exercise device that could be carried in a suitcase. This required considering both physical and non-physical characteristics like function, structure, form, surface, materials, process, and system.

The lecture moved on to knowledge transfer by comparing analogies to problem solving, and learning how analogies can strengthen solutions for the task at hand. Examples include comparing a human's blood clot to a traffic jam when looking at the whole map of the United States. This is meant to demonstrate how biological systems can be linked to engineered systems. The lecture then explained what bio-inspired design is and is not, and the two design paths of problem-driven and biology-driven; the final part of the lecture with in-class learning activities was explicitly on the problem-driven approach.

The remainder of the lecture focused on either the C-K approach or the BI approach. Each approach was demonstrated by two in-class learning activities. The first involved a detailed account of how to apply the approach using an example from the literature (Flectofin hingeless louver system for C-K, Entropy carpet tiles for BI), and students were expected to follow along with the respective bio-inspired design template provided. The second activity focused on the propulsion subsystem of a human powered vehicle (course project design problem) and was less structured to allow students to work together in small groups to complete the activity, with the instructor showing example solutions for each step of the method as students completed them. The second learning activity topic and solution were the same for both approaches.

Following the lecture, students in both groups were given an assignment involving four tasks: (1) creating a propulsion sub-system concept for a human powered vehicle based on inspiration from the Northern Leopard Frog using the instructional approach they had been exposed to; (2) creating a concept for any human powered vehicle sub-system (e.g., steering, structure, seating, braking) using a biological system of choice using instructional approach they had been exposed to; (3) creating a full system concept using one or both of the biologically inspired sub-systems from tasks 1 and 2 and the team's morphological matrix; and (4) completing reflection questions about bio-inspired design. The C-K approach sections were given the C-K theory mapping template (Figure 4) with guidelines that encouraged students to dive deeper into biological information and to consider different attributes of the biological system. The BI sections were shown how the process is split into 4 categories: scoping, discovering, creating, and evaluating, with emphasis that the process is iterative. Both groups were shown AskNature.org as a resource for finding inspiration and learning about biological systems. Overall, students incorporated the

bio-inspired concepts into their human powered vehicle designs to create new concepts for their final human powered vehicle. The comparative study is performed on the output of tasks 1 and 4.

## 5. Analysis, Results and Discussion

In this section, the analysis and results of the data collected during the comparative study are presented. The section concludes with a discussion of the results.

### 5.1 Task 1 - Creating a single propulsion sub-system concept

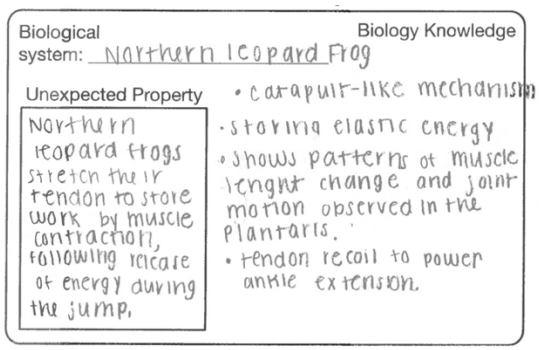
Both groups were tasked with creating a single propulsion sub-system concept for a human powered vehicle based on inspiration from the Northern Leopard Frog. The output from this task for the C-K group was a completed C-K map, and for the BI group a response to each of the eight steps of the Biomimicry Institute approach. Incomplete assignments were removed prior to the analysis. Concept quality was analyzed in two ways: (1) qualitative affinity sorting to identify trends and (2) statistical analysis of concept scores.

Two themes of biological inspiration and engineering implementation were chosen for affinity sorting because prior studies have shown that bio-inspired design often leads to concepts that imitate the biological system appearance but are not necessarily sensible for the problem [17, 39]. High quality concepts are judged to use biological principle information as inspiration for design and to make connections to engineering principles. Lower quality concepts are judged to closely mimic the observable aspects (e.g., physical attributes, movements) of a biological system and to present less practical engineering solutions.

Biological inspiration data was determined from the biological knowledge box of the C-K map and the abstract step of the BI design lens. Biological imitation is defined as directly copying observable aspects of the biological system, whereas inspiration is focused more on learning about the biological system on a deeper level. Table 2 summarizes the biological inspiration affinity sort. The categories of tendons and muscles include concepts that illustrate deeper learning of how the frog's legs propel it forward when jumping. The leg strength category illustrates the blending of learning and copying the frog legs, whereas the legs category concepts focus exclusively on the physical characteristics of the legs. Examples from the category other include frog bones, frog posture, and jumping distance. Figure 5 provides two representative examples of student work from the affinity sort that align with the categories given in Table 2.

Table 2: Affinity Sorting of Biological Inspiration

| | Tendons | Muscles | Leg Strength | Legs | Other |
|---|---|---|---|---|---|
| Total | 38 | 9 | 11 | 20 | 10 |
| BI | 9 | 1 | **7** | **15** | **8** |
| CK | **29** | **8** | 4 | 5 | 2 |
| Inspiration VS. Imitation | | | | | |



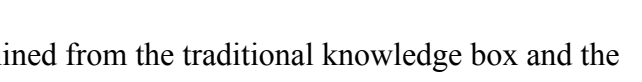




Figure 5: Example Student Work for Biological Inspiration Affinity Sort. Left: Tendons Example. Right: Legs Example.

Engineering implementation data was determined from the traditional knowledge box and the sketch of the C-K map and steps of the creating phase of the of the biomimicry design lens. Table 3 summarizes the engineering implementation affinity sort. The category connects to existing technology includes concepts that include technology that is feasible and on the market, such as leg press mechanisms. The elastic/kinetic energy category includes concepts that focus on the tendon and muscle functions of energy storage and release primarily through springs or elastic bands. The frog motion category includes concepts that require the rider to move like a frog or the vehicle moves like a frog. Concepts in the category other do not provide enough information to discern if it fits within another category. Some concepts were not bio-inspired and one was not human powered. Figure 6 provides two representative examples of student work from the affinity sort that align with the categories given in Table 3.

Table 3: Affinity Sorting of Engineering Implementation

| | Connects to existing technology | Elastic/Kinetic Energy | Frog motion | Other | Not Bio-inspired | Not a HPV |
|---|---|---|---|---|---|---|
| Total | 28 | 32 | 14 | 4 | 9 | 1 |
| BI | 10 | 13 | **9** | 2 | **5** | **1** |
| CK | **18** | **19** | 5 | 2 | 4 | 0 |

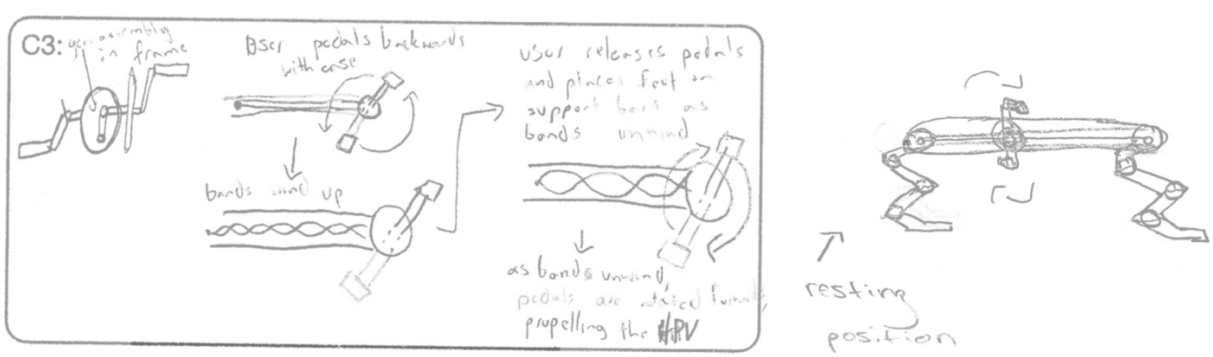



Figure 6: Example Student Work for Engineering Implementation Affinity Sort. Left: Elastic/Kinetic Energy Example. Right: Frog Motion Example.

To further investigate the research question, a quantitative analysis was performed on the scores assigned to each concept. Each concept was scored by two raters on a 0-3 scale for the metrics of biomimicry and feasibility. The scoring for the biomimicry metric is as follows: 0 for directly copying the biological system, 1 if between a direct copy and information extraction, 2 if biological information was extracted, and 3 if biological information was abstracted. The scoring for the feasibility metric is as follows: 0 for not technically feasible, 1 if feasible but difficult for the context, 2 if not difficult for the context and not existing outside the dataset, and 3 if existing outside the dataset [44]. The two scores were averaged and parametric (student t test) and non-parametric (Wilcoxon-Mann-Whitney Rank Sum) statistical tests were performed on the averaged values. Table 4 summarizes the statistical results. The probability values indicate the confidence that the differences between mean scores for each criterion are significantly different.

Table 4: Mean and Probability Values for Statistical Tests

| | Mean scores (N) | | p values | |
|---|---|---|---|---|
| | C-K | BI | Student t test | Wilcoxon-Mann-Whitney Rank Sum |
| Biomimicry | 1.57609 (47) | 1.09459 (41) | p=0.003268 | p=0.00584 |
| Feasibility | 2.15217 (47) | 1.74324 (41) | p=0.01319 | p=0.01235 |

### 5.2 Task 4 – Individual reflection questions about the content and process

Both populations were required to answer both Likert scale and open-ended reflection questions as part of the assignment. Table 5 provides the question sets.

Table 5: Reflection Questions of Task 4

| **Likert Scale Questions** | **Open-ended Questions** |
|---|---|
| Q1: How effective was the bio-inspired design approach taught in class in helping you to identify a biological organism to help solve the engineering design task? | What did I learn about the content (biology)? |
| Q2: How effective was the bio-inspired design approach taught in class in helping you to understand the underlying principle of the biological organism? | How did I learn the content? |
| Q3: How effective was the bio-inspired design approach taught in class in helping you to transfer knowledge learned from a biological organism to the engineering design task? | What am I going to do with the content? |
| Q4: How effective was the bio-inspired design approach taught in class in helping you to apply the biological inspiration to your engineering design task? | |
| Q5: How effective was the design approach overall in demonstrating the value of biology as a resource for finding solutions to engineering design problems? | What did I learn about the process |

| | |
|---|---|
| | (bio-inspired design)? |
| Q6: How effective was the design approach in motivating you to learn more about how biological systems have solved problems in different engineering categories? | How did I learn the process? |
| Q7: How engaged were you in learning the bio-inspired design process? | What am I going to do with the process? |

For each of the Likert scale questions, students were instructed to answer on a scale of 1 to 5 (1 being low, 3 being neutral, 5 being high). The responses were averaged and are reported in Table 6.

Table 6: Mean Values of Responses to Likert Scale Questions of Task 4

| | **Q1** | **Q2** | **Q3** | **Q4** | **Q5** | **Q6** | **Q7** |
|---|---|---|---|---|---|---|---|
| **BI** | 4.01 | 3.88 | 4.00 | 3.92 | 4.46 | 4.14 | 4.17 |
| **CK** | 3.98 | 3.91 | 3.98 | 3.97 | 4.42 | 3.98 | 4.15 |

### 5.3 Discussion

Affinity sorting resulted in distinct trends between the two groups. Students from the C-K group tended to take inspiration from non-observable biological information (e.g., how the tendons and muscles function). Meaning they learned information beyond the surface level about what allows the frog to propel itself. When applying the biological inspiration, they were more likely to utilize existing technology such as rowing machines, leg presses, elliptical machines, and crank arms in their concepts as well as abstract the functional characteristics of the biological inspiration. This demonstrates the ability to make connections across the domains for practical applications. Students in the BI group tended to fixate on the number, shape, strength or motion of the frog legs. They were also more likely to generate concepts that imitated how the frog looks or acts or requires the user to act like a frog. While the BI group was more likely to generate unique ideas, they were also more likely to generate concepts that are not relevant to the process or problem.

Statistical analysis of concepts using an objective scoring method supports the trends observed through affinity sorting. Statistical significance was achieved for the hypothesis that the C-K approach would produce higher quality concepts than the Biomimicry Institute approach. Statistical significance was found at $p=0.01$ (both tests for biomimicry metric) and $p=0.05$ (both tests for feasibility metric). Meaning the C-K group produced concepts that were more biologically inspired and technically feasible.

In this preliminary analysis, it was found that the C-K group produced results of higher quality through multiple analyses. Connections between biology and engineering are influenced by alignment with mental representations or mental models [45]. Mental models influence the level of abstraction that designers use when transferring knowledge across domains. We cannot

explain why certain biological information or engineering implementation was dominant over others with respect to the student concepts; however, the data shows that when visually guided through the thought processes of bio-inspired design with the C-K map students fixated less on irrelevant information. As compared to the BI group, the C-K group made deeper connections between biology and engineering for problem solving. The C-K mapping template provides a visually guided approach and allows a novice designer to map the mindset of bio-inspired design.

Interestingly, the results of the self-reported perception on the effectiveness of the bio-inspired design approach learned are the same between both groups for five of the seven questions. Students in the C-K group rated Q5 and Q6 lower which is opposite of the task 1 analysis results. This could be due to the fact that the C-K mapping template focuses on a single biological system at a time. Students reported that the methods helped them to understand the biological system and transfer the knowledge learned to the engineering design task. Meaning cross-disciplinary connections were made to facilitate problem solving. Students seem to enjoy the topic of bio-inspired design regardless of the method taught. Overall, students recognized the value of taking inspiration from nature for solving engineering problems, and many would use the approach again in future classes or projects.

## 6. Conclusions and Future Work

This paper reports on the preliminary analysis results from testing the hypothesis that the C-K approach would result in higher quality design concepts. It was found that the C-K group generated concepts that more closely resembled biological inspiration, meaning learning from nature to innovate rather than copying, and successfully abstracted biological system principles to create high quality concepts. Whereas the BI group generated concepts that more closely resembled biological imitation, which tended to fixate on observable features and produced concepts that look or act like the biological systems. Statistical significance was achieved for the hypothesis using the metrics of biomimicry and feasibility. The study findings provide conclusive evidence of learning impact and support design theory based bio-inspired design pedagogy. Integrating bio-inspired design with the traditional design curriculum has numerous benefits, but teaching methods are limited. We believe the results of this research can inform engineering educators on how to effectively teach bio-inspired design to engineers.

Future work includes statistical analysis of the task 2 concepts and qualitative content analysis of the open-ended reflection questions. The responses to the open-ended questions will be analyzed using a qualitative content analysis approach to provide contextual information to the quantitative data [46]. Responses will be reduced to their smallest meaningful unit and given a code. Codes will be grouped into categories followed by definition of themes from the categories. Additional future work includes testing the C-K theory-based instructional resources at other institutions to evaluate transferability.

## 7. Acknowledgements

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. This material is based upon work supported by the National Science Foundation under Grant No. 1504612. We would like to thank the James Madison University engineering students that participated in the study.

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Nagel JK, Pittman P, Pidaparti R, Rose C and Beverly C (2016) Teaching bioinspired design using C–K theory. *Bioinspired, Biomimetic and Nanobiomaterials*, http://dx.doi.org/10.1680/jbibn.16.00013

**Bioinspired, Biomimetic and Nanobiomaterials**

**Research Article**
Received 05/04/2016 Accepted 17/10/2016
**Keywords:** bioinspired/biomimicry/design

ice | science



ice Institution of Civil Engineers publishing

# Teaching bioinspired design using C–K theory

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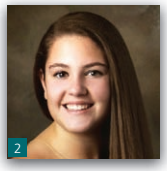


**The engineer of 2020 is expected to not only offer technical ingenuity but also adapt to a continuously evolving environment while being able to operate outside the narrow limits of one discipline and be ethically grounded in solving the complex problems of the future. To address the competencies of the future engineer, undergraduate education must train students to not only solve engineering challenges that transcend disciplinary boundaries but also communicate, transfer knowledge and collaborate across technical and non-technical boundaries. One approach to training engineers in these competencies is teaching biomimicry or bioinspired design in an engineering curriculum, which offers relevance to professional practice as well as an effective hook to frame complex, cross-disciplinary problems. This research aims to address the need for undergraduate student training in multidisciplinary design innovation through the creation of instructional resources grounded in the concept–knowledge theory that scaffolds discovery and knowledge transfer processes such that natural designs can be used to inspire engineering solutions. Qualitative content analysis of second-year engineering student reflection statements shows that the instructional resources resulted in significant learning and engagement.**

## 1. Introduction

It is well known that engineering involves integrating broad knowledge towards some purpose, generally to address a need or solve a problem. As the society is moving into a global future, engineers can no longer isolate themselves and must be prepared to work across disciplinary, cultural, political and economic boundaries. Every day, engineers are confronted with complex challenges that range from personal to municipal to national needs.[1] The ability for future engineers to work in multidisciplinary, interdisciplinary and transdisciplinary environments will be an essential competency.[2] Furthermore, with greater emphasis being placed on understanding social, economic and environmental impacts of engineered solutions, another essential competency is the cognitive flexibility to think about the whole system at different levels of fidelity and at different time scales.[3,4] Undergraduate education must train students to not only solve engineering challenges that transcend disciplinary boundaries but also communicate, transfer knowledge and collaborate across technical and non-technical boundaries. One approach to achieving this goal is teaching biomimicry or bioinspired design in an engineering curriculum.[5] Bioinspired design encourages learning from nature to generate innovative designs for man-made technical challenges that are more economical, efficient and sustainable than the ones conceived entirely from first principles.[6]

Incorporating other science, technology, engineering and math (Stem) disciplines into complex engineering problems will create a new context for undergraduate students to apply knowledge that they already have. Most students that go into engineering have secondary school-level training in biology. Adding biomimicry into the engineering curriculum encourages students to utilise and build on their prior knowledge, which fosters making connections and recognising interrelationships across Stem disciplines.[7,8] Moreover, requiring knowledge transfer across domains as well as organising that knowledge into logical constructs helps to develop future flexibility and adaptive expertise that will facilitate

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innovation and efficiency.[9,10] Having to retrieve and transfer knowledge from domains outside of engineering forces students to adapt to unfamiliar languages and content formats (which addresses non-technical skills) in order to apply biological information intelligently to engineering problems (which addresses technical skills). Additionally, biomimicry touches on many areas of engineering, including electrical, mechanical, materials, biomedical, chemical and manufacturing systems, which makes it applicable in a wide range of engineering programmes, from discipline-specific to general ones.

Showing engineering students the significance and utility of bioinspired design is easy. Teaching them how to create a bioinspired design without also requiring them to be fully trained as biologists is much more difficult. Teaching bioinspired design in an engineering curriculum relies on either the impromptu application of biological inspiration or research methods and tools that are tied to specific engineering design methodologies. Typically, within the classroom, a tool or method is presented with an example that illustrates the technique and students are expected to practice the inherent knowledge transfer steps required to understand the underlying principle. Much less is known about how to guide students effectively in the knowledge transfer steps that are so crucial to moving between the engineering design space and the biology space. Students are set up to make the creative leap across these spaces, but they are not supported in the actual leap. Thus, analogy use/misuse, mapping and transfer are repeatedly cited as the major challenges with teaching bioinspired design to engineers.[11–19] This is an important gap to address since effective navigation between engineering design and biology spaces builds connections that facilitate innovative design and increases engineering students' cognitive flexibility, creativity and adaptive problem-solving skills.[20] The research presented in this paper aims to address this gap through developing effective instructional resources grounded in the concept–knowledge (C–K) theory for implementing bioinspired design in an engineering curriculum, with particular focus on assisting engineering students with knowledge transfer between the domains of engineering and biology.

## 2. Background material

In this section current approaches to teaching biomimicry in an engineering curriculum are shared as well as background knowledge on the C–K theory, which is used as the basis for the instructional resources.

### 2.1 Teaching bioinspired design

In response to the increased emphasis on adaptable and sustainable design by professional societies, the industry and today's global marketplace, engineering programmes in the USA and internationally are increasingly expanding the scope and focus of their curricula to include bioinspired design topics and projects. The inclusion of bioinspired design expands cross-disciplinary and system thinking skills and has been integrated into engineering programmes at the module, project or course level.[7,8,11,14–16,18–27] While instruction in bioinspired design is quite common in engineering programmes at the graduate level, it is exciting to note that bioinspired design instruction is also being incorporated into curricula at the undergraduate level.

Multiple institutions offer engineering courses in bioinspired design or interdisciplinary courses that bring together students from Stem and art that span an academic term. Probably the most well-known institution is Georgia Institute of Technology (Georgia Tech), which offers multiple courses and a certificate through the Center for Bio-inspired Design.[28–30] The undergraduate interdisciplinary course is co-taught by faculty from the biology and engineering departments and admits junior- and senior-level students from all fields of engineering and biology. Two processes for bioinspired design, problem-driven and solution-driven, are taught in the course, and analogies are formed through functional decomposition, similar to functional modelling in engineering design.[29] More recently, the four-box method that identifies function, operating environment, constraints and performance criteria as dimensions for matching biological analogues with the design problem has been implemented.[31] Students work in interdisciplinary teams on assignments and projects throughout the course. Honours-level undergraduate courses similar to the one at Georgia Tech have been offered at institutions such as Virginia Polytechnic Institute and State University.

The mechanical engineering department at Montana State University offers a senior-level technical elective on bioinspired engineering.[14] The course covers relevant bioinspired design and engineering design processes with a focus on structures and materials from both nature and engineering. The practices taught in the course include reverse engineering and tabulating a variety of relationships. Thus, the focus is more on comparison than innovation. Texas A&M University is currently developing an undergraduate course to introduce interdisciplinary engineering students to multiple methods of bioinspired design.[25] The course will be an elective in the mechanical engineering curriculum that focuses on breadth of approach rather than depth, exposing students to the state of the art in bioinspired design research tools and methods. At the Olin College of Engineering, all students take a course that introduces bioinspired design in their first academic term. The course is called 'Design Nature' and is an introduction to the engineering design process that also weaves in concepts from nature. Students complete individual and team projects in the course. Similarly, all first-year engineering students at the University of Calgary are introduced to biomimicry in their design and communication course.

At Kettering University, in the Industrial and Manufacturing Department, biomimicry is integrated into an ergonomics course through problem-based learning.[23] Students work individually on projects by using the Biomimicry Innovation Tool, which blends aspects of problem-based learning, innovation, biomimicry and ergonomics into a single student experience. They present their bioinspired concept at the end of the course. The University of Maryland offers a course in biomimetic robotics as a senior elective in the mechanical engineering programme.[19] Students

study biological locomotion and how it can inspire efficient mechanisms of motion.

Non-US institutions that offer courses in biomimicry are concentrated in Europe. Germany alone has 16 universities that offer lectures, seminars, electives, core courses or degrees related to biomimicry or biomimetics.[32] Saarland University offered multiple courses and lectures in the area of technical biology developed by Professor Nachtigall, but these were abandoned following his retirement.[32] Hochschule Bremen offers an international bachelor's degree in biomimetics that blends biological and engineering science through a practice-based, interdisciplinary course of study with courses on materials, structures and transport systems.[33] One course, 'Locomotion', investigates the biological drive mechanisms of animals through the creation of kinematic and dynamic models of technical and natural structures. The course requires laboratory experiments as well as discussion on animal rights' protection policy and ethics.[34] At the University of Bath, fourth-year mechanical engineering students can take a course in biomimetics. Courses on bioinspired materials are offered at Nanyang Technological University in Singapore, ETH Zurich, Eötvös Loránd University in Budapest and KTH Royal Institute of Technology in Stockholm. A unique course on biomimetic biomaterials and technologies for the purposes of medical bioengineering is offered at Grigore T. Popa University of Medicine and Pharmacy in Romania.[35]

Bioinspired design concepts and examples have been used by many institutions to educate students on design innovation and as another source of design inspiration. These institutions include Oregon State University, University of Georgia (UGA), James Madison University (JMU), Purdue University, Clemson University, Penn State University–Erie, University of Maryland, Indian Institute of Science, University of Toronto, Dalhousie University, Freiburg University and École Centrale Paris, to name a few. Often the instruction is across less than four lectures, which reduces the burden of integration into existing courses. These institutions also require engineering students to complete assignments or a project involving bioinspired design to practice the technique and demonstrate its value. Integration occurs at the freshman through the senior level, in a variety of departments, and primarily depends on when engineering design is offered in the curriculum. Consequently, varying levels of instruction and support are provided to the students, and many rely on the resources provided by the Biomimicry Institute, such as the database AskNature.org. This points to the lack of engineering-focused, evidence-based instructional resources available to faculty that wish to integrate bioinspired design into their courses.

### 2.2 C–K theory

The C–K theory, introduced by Shai *et al.*,[36] Hatchuel *et al.*[37] and Hatchuel and Weil,[38] integrates creative thinking and innovation by utilising two spaces: (*a*) the knowledge space (*K*), a space containing propositions that have a logical status for the designer, and (*b*) the concept space (*C*), a space containing concepts that are propositions or groups of propositions that have no logical status (i.e. are undetermined) in *K*.[36–40] This means that when a concept is formulated, it is impossible to prove that it is a proposition in *K*. Rather, concepts are used to generate questions and the research to answer those questions will generate new knowledge that will provide new attributes for new concepts. The wider your initial knowledge is, the higher the number of feasible concepts. However, the final result of the concept generation process is initially unknown. The design path is defined as a process that generates concepts from an existing concept or transforms a concept into knowledge. Although specific tools are not embedded, the C–K theory has shown to reduce fixation and improve the knowledge and creativity of the user.[36–40]

There are four operations allowed: expansion of each space ($C \rightarrow C$, $K \rightarrow K$); conjunction, meaning when a concept proposition is tested and leads to new knowledge ($C \rightarrow K$); and disjunction, meaning when a new concept is generated from existing knowledge ($K \rightarrow C$). Concepts can be partitioned or included, but not searched or explored in the *C* space. Adding new properties to a concept results in the concept being partitioned into sets or subsets of concepts. The reverse, subtracting properties from a concept, results in subsets being included into the parent set. After partitioning or inclusion, concepts still remain concepts ($C \rightarrow C$), but they can also lead to the creation of new propositions in *K* ($C \rightarrow K$). The combination of knowledge and addition of new discoveries expands the knowledge space ($K \rightarrow K$) and can result in new concepts ($K \rightarrow C$). Innovation is the direct result of the two operations that move between the spaces: using the addition of new and existing concepts to expand knowledge and using knowledge to expand concepts. The C–K theory thus provides a framework for a designer to navigate the unknown, to build and test connections between the knowledge and concept spaces (analogies) and to converge on a solution grounded in theory combined with new knowledge.

The C–K theory emphasises connection building as well as exploration and expansion of both spaces to iterate to a better solution. Knowledge is therefore not restricted to being a space of solutions; rather, it is being leveraged to improve understanding of innovative designs. Moreover, the C–K theory requires explicit documentation of the design path, thus inherently modelling cross-domain linkages. Utilising the C–K theory to create instructional resources for teaching bioinspired design that integrate biology, engineering and design establishes a two-way connection between engineering and biology and illustrates how knowledge transfer processes can lead to design innovation. The C–K theory is adaptive and generalisable across scientific domains, which makes it amenable to a wide range of engineering problems as well as programmes.

## 3. Experimental

Utilising the C–K theory to create instructional resources for teaching bioinspired design that integrates biology, engineering and design establishes a two-way connection between engineering and

biology and illustrates how knowledge transfer processes can lead to innovative solutions.[41] Although the C–K theory is an established theory, no instructional resources for how to use it in a classroom exist; thus, a major part of this research was to design the instructional resources themselves. Because the C–K theory is a visual approach to structuring the discovery process of learning from the knowledge and concept spaces, a C–K mapping template (as shown at the top of Figure 1) was created. This template is an adaptable instructional resource that promotes discovery by facilitating the knowledge transfer processes of bioinspired design going from biology to engineering (biology-driven direction) as well as from engineering to biology (problem-driven direction) if starting from the knowledge or concept side, respectively. An accompanying set of guidelines for filling out the template was created to assist novice learners. As an adaptable resource, the template can be used at multiple learning levels (e.g. novice, intermediate, expert) by adding or subtracting supplemental information and by choice of design path. The instructional resources created using the C–K theory framework are outlined in Table 1.

In fall of 2015, the lead author instructed a second-year engineering design course (total $n$ = 23) that incorporated each

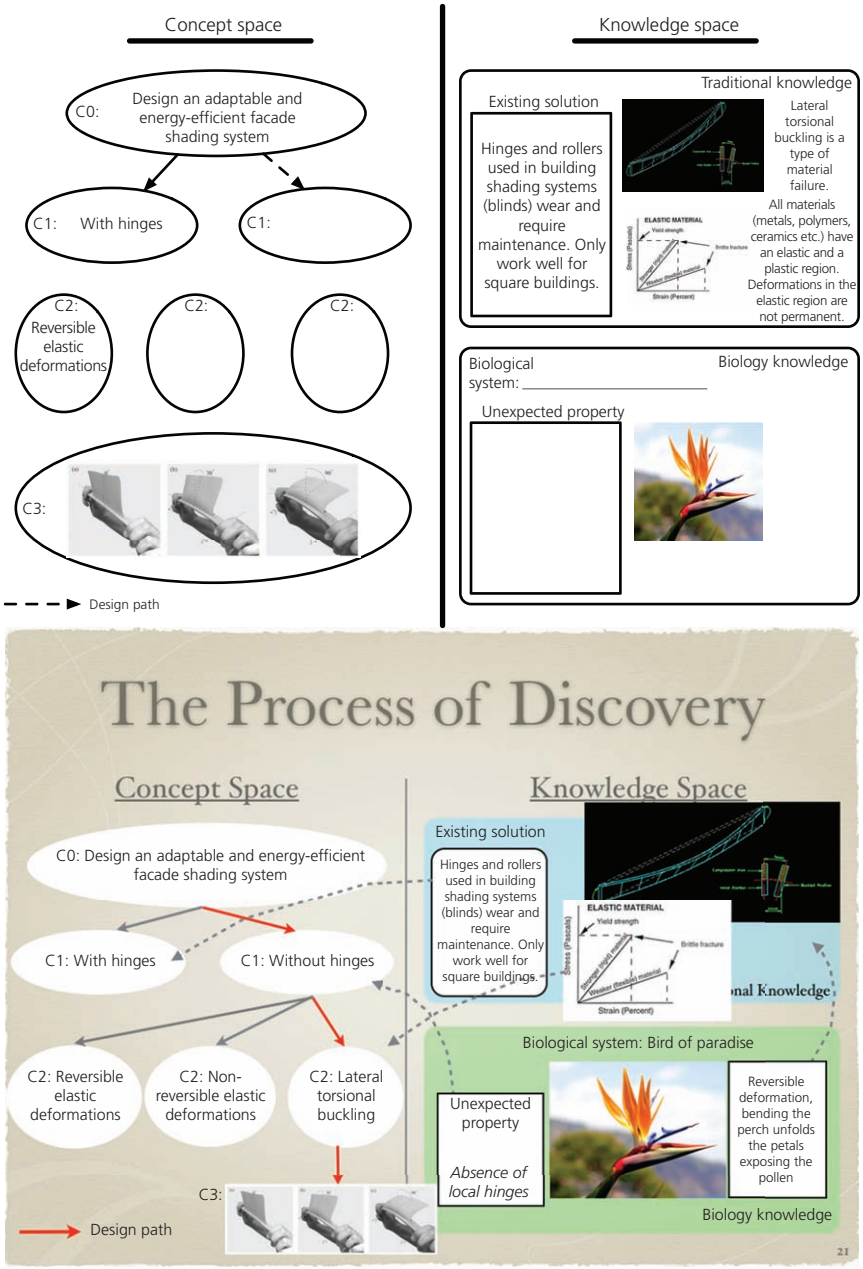


**Figure 1.** Template (top) and slide (bottom) from teaching module for first learning activity

| Instructional resource | Description |
|---|---|
| Teaching module | Demonstrates the breadth of biological inspiration, models the development of cross-domain linkages, scaffolds the knowledge transfer processes between domains and utilises analogies |
| C–K mapping template and guidelines | Guide students through the two major paths to a bioinspired design (biology-driven and problem-driven) and scaffold the knowledge transfer processes between domains |
| Learning activities | In-class exercises that promote active learning of bioinspired design |
| Assignments | Students practice developing cross-domain linkages to and from both domains for solving engineering problems |

**Table 1.** Summary of instructional resources

instructional resource listed in Table 1. The second-year engineering design course focuses on the theory, tools and methods of the engineering design process. Students work in teams to design a human-powered vehicle (HPV) for a person in the community with cerebral palsy.

The developed teaching module introduces bioinspired design as a design philosophy and provides several examples of how biological systems were used as inspiration for innovative solutions. Students learn about the two major paths to a bioinspired design, biology-driven and problem-driven, as well as how analogies are used to assist with transferring the knowledge from biology to engineering. To scaffold the students in their application of bioinspired design, two problem-driven examples using the C–K theory were provided with accompanying learning activities using the C–K mapping template. The first learning activity focused on the hingeless facade shading mechanism, Flectofin, inspired by the bird of paradise flower.[42] Shading buildings with irregular geometries is very difficult since most sun protection systems have been developed for planar facades and include the use of hinges. The pollination mechanism of the bird of paradise flower offers inspiration based on the elastic kinematics of plant movements. After the initial problem is explained, students are provided a partially filled-in template to complete during the explanation of the example as shown in Figure 1. This scaffolds the students through the C–K theory mapping process without burdening them with the theory. Students are walked through the thought processes and analogies of the discovery process for arriving at a bioinspired solution by using the C–K theory framework as shown in Figure 1. The slide animations build up the information and demonstrate the four types of operations ($C \rightarrow K$, $K \rightarrow C$, $K \rightarrow K$, $C \rightarrow C$) that capture all known design properties, including creative processes, and explain the chaotic, iterative nature of real and practical design work starting from the C0 level and arriving at the C3 level in the concept space. Furthermore, the grey dashed arrows provide insight on how concepts are elaborated by using knowledge and when the operators are used. The example concludes with explaining the technical innovation that resulted from the process of discovery.

The second problem-driven example and learning activity is focused on the propulsion subsystem of an HPV. This is meant to scaffold the students in not only using the template, but also recognising how the approach can be applied to their course project in a meaningful way. During this learning activity, the students were provided a blank copy of the C–K mapping template and a copy of the guidelines. Students work in small teams with more independence this time and work through each step of the guidelines while the instructor roams the room to answer questions. If several students are struggling, the instructor addresses key points in the process of filling out the template with the whole class. When most teams have completed the step, the next layer of information is shown on the slide to demonstrate how an expert would go through the process and to discuss how the connections or linkages are formed between biology and engineering. Again, the slide animations build up the information and demonstrate the four types of operations that capture all known design properties, including creative processes, and explain the chaotic, iterative nature of real and practical design work.

All assignments in the second-year engineering design course tie to a year-long course project of developing an HPV for a client in the community that has cerebral palsy; thus, a separate project was not defined for this implementation. To integrate bioinspired design into the HPV design project, each member of a team applied bioinspired design to a different subsystem (e.g. propulsion, steering, braking) of their design to showcase a variety of design problems and analogies that enable bioinspired design. All students completed the C–K mapping template three times, twice in class as part of learning activities to understand the process of discovery and again in their assignment to scaffold application to the HPV. The developed assignment that complements the teaching module and learning activities for the second-year engineering design course includes three tasks: (*a*) completing the C–K mapping template for an HPV subsystem, (*b*) using the sketches at the C3 level of the template along with the team-generated morphological matrix to create a fully HPV concept and (*c*) a W/H/W reflection essay answering three questions about the content and process. The W/H/W reflections require learners to reflect on and respond to three questions: 'What did I learn?', 'How did I learn it?' and 'What will I do with it?' These three prompt the second problem-driven example structure reflection so that learners focus on concepts, knowledge, skills, processes and engagement of learning. The W/H/W reflections provide formative snapshots of learning and

application to explore the connections across concepts and domains that learners are making as they progress through the material.

For this paper, the W/H/W reflection questions were analysed to identify trends in student learning outcomes in bioinspired design education in an engineering design course. Fifteen (65%) students consented to participate in the research. Transcriptions of the reflection questions for consenting participants were de-identified and analysed by using qualitative content analysis. Qualitative content analysis identifies themes in the student reflections. This involved reducing the participants' comments to their smallest meaningful units, coding these units, grouping the coded units into categories and then grouping the categories into different themes.[43,44] The following section presents the results of the qualitative content analysis and a discussion of the findings.

## 4. Results and discussion

The student responses to the six reflection questions resulted in 206 (108 for content questions and 98 for process questions) unique/coded meaningful units. Multiple themes and categories emerged for each question based on coded meaningful units. Tables 2 and 3 show the coded meaningful units produced for each reflection question as they were grouped by category ($N$ = number of supportive coded meaningful units in each category) and theme ($N$ = number of supportive categories in each theme). The qualitative content analysis shows the trends in student responses through aggregated data such that identity of the student is protected.

Each question has one or more highly supported themes ($N > 10$) and one theme with less support ($N < 10$). The highly supported themes related to learning about content (biology) are that students learned detailed information about their chosen biological system, established cross-domain linkages and overall valued what can be learned from biology and applied to engineering problems. Most categories found under these themes were fully anticipated. One unanticipated category from one student was that learning about biology helped in gaining further knowledge about a specific subsystem of the HPV. In other words, the assignment allowed the student to learn more about engineering through biology. Students learning the content through non-course resources was anticipated, as the instructional resources did not provide that information. Also, with respect to what students will do with the content, application to the course project through the assignment was anticipated. It is encouraging that some students recognised other applications of the learned content.

The highly supported themes related to learning about the process (bioinspired design) are that students valued the inclusion of biological inspiration during the design process and that inspiration from nature can help solve design problems, even though sometimes more analysis is required than initially thought. It was anticipated

| What did I learn about the content? | How did I learn the content? | What am I going to do with the content? |
|---|---|---|
| T1: Valued what can be learned from nature and biology (17) | T1: Scholarly or external resources (31) | T1: Apply to immediate problem – class project (16) |
| Nature has surprisingly complex systems that work well in particular since they have been around for years (7) | Further exploration or analysis of information beyond website provided (21) | Apply to class assignment – HPV (12) |
| Nature has a lot to offer for potential solutions (5) | Independent research using website provided (9) | Maybe apply it to class (HPV) but question feasibility or necessity (4) |
| Nature has attributes that can be iterated easily into design (5) | Discovery Channel television special (1) | |
| T2: In-depth understanding of chosen biological system (14) | T2: Course learning resources (4) | T2: Facilitate a future design path (11) |
| Detailed biological information on specific topic (11) | Class examples (1) | Apply to other problems (6) |
| Gained knowledge about biological subsystems (3) | Filling out C–K mapping template (3) | Gain new perspective when designing (4) |
| T3: Cross-domain linkages (11) | | Put it on a C–K map (1) |
| Formed a connection between HPV design and chosen biological subsystem (10) | | |
| Gained further knowledge about specific subsystem of HPV (1) | | |
| T4: Biology is not always applicable (4) | | |
| Biology does not relate to class assignment (3) | | |
| Nothing (1) | | |

**Table 2.** Themes and frequencies of content reflection questions

| What did I learn about the process? | How did I learn the process? | What am I going to do with the process? |
|---|---|---|
| T1: Valued the inclusion of biology in engineering design (22) | T1: Course learning resources (20) | T1: Facilitate a future design path (20) |
| Keeps the design space open to more ideas (12) | Using the C–K mapping template (11) | Use it when designing or problem-solving in the future (14) |
| Bioinspired design is a process similar to the engineering design process (10) | Following the class example (8) | Use method to expand design space (3) |
| T2: Recognised knowledge transfer between domains for problem-solving is possible (17) | Transforming the template information into a drawing (1) | Use existing biology knowledge to help understand engineered components and systems (2) |
| Biology can inspire solutions to problems (10) | T2: External or other resources (13) | Use in all aspects of life (1) |
| More biological analyses are needed than anticipated (5) | Previous knowledge (5) | T2: Apply to immediate problem – class project (3) |
| Facilitates connecting an engineering sub-system to a biological system (2) | Independent research of online resources (5) | Use for class assignment – HPV (2) |
| T3: Bioinspired design is not always applicable (3) | Applying an engineering problem-solving approach (2) | Continue research (1) |
| Sometimes bioinspired design is not feasible (2) | Existing bioinspired designs (1) | |
| Nothing new (1) | | |

**Table 3.** Themes and frequencies of process reflection questions

that students would learn the process through course instructional resources, as the instructional resources were created for that purpose. Students were engaged in the learning of bioinspired design as evidenced by the majority of responses linking to future design applications. An unanticipated category from two students was that using existing biology knowledge helps to understand engineered components and systems, which was also found in a student response to what was learned about the content. This emergent trend was unexpected and points towards the significance of teaching bioinspired design in an engineering curriculum.

Comparison of the responses between Tables 2 and 3 by type of question reveals a positive influence of the C–K theory-based instructional resources. The strongest supported themes link well to the objectives of the research, which are to facilitate the knowledge transfer process of bioinspired design, to assess engagement in learning and to increase students' abilities to recognise and formulate interrelationships across disciplinary boundaries and to create bioinspired designs. The reflection analysis indicates that the assignment exposed the students to a variety of design examples in nature, scaffolded the discovery and knowledge transfer processes required to create bioinspired designs and promoted significant learning about biology and applying biology during design as well as engagement. Also, the bioinspired design teaching module, learning activity and assignment were generally well received by students based on reviews of the student assignments and from conversations with the students outside of class. Students found the topic and the C–K mapping process engaging and useful. Many commented in their reflection essays that they found the technique valuable and will use it in future opportunities that require innovative solutions or problem-solving. Additional positive trends in the essays include students commenting that they had never considered nature as a source of design inspiration before and that this process opened up their eyes to so much potential, how impressed they were with the variety of biological systems that can inspire innovations and feelings of creativity and that it was fun or exciting. The only negative category in the essays was the feeling that bioinspired design was not necessary for, or applicable to, the task at hand, and this category was weakly supported ($N = 4$ and 3).

A variety of supportive methods were used to ensure access to information and engagement and encourage students to use their opportunities to engage. The information was presented using multiple modalities including verbal, visual and kinaesthetic. The lecture engaged the whole class, while the in-class activities facilitated smaller-group and individual work. Guided practice was used in class during the activities and independent practice was required in the assignment. One alternative teaching method would be to have a biology faculty member teach biological phenomena in terms of structure–function relationships, much the same way that these are taught in comparative anatomy classes, and have the students use these as the background for abstracting the engineering principle and finding an application.

This paper summarises the progress to date that has been made at JMU with implementation plans for UGA. Analysis of the reflection statements is complete. Future work includes developing

a rubric for grading the student-generated bioinspired designs that were produced in the assignment by using C–K mapping templates. This rubric would be designed to score the depth and detail of the student effort to generate a design from a biological example, as well as the plausibility of the final design from an engineering point of view. This rubric would also allow for comparisons between what students actually accomplished and how they perceived the value of the educational experience in their reflection essays. Additionally, the rubric would allow for comparison of student work across institutions and thus provide an objective measure for judging the transferability of instructional materials between JMU and UGA. Additional future work includes administering two controlled experiments to test the C–K theory-based teaching approach against an alternative bioinspired design teaching method to obtain conclusive quantitative evidence of its learning impact.

## 5. Conclusion

Engineering students find bioinspired design exciting, and it offers relevance to professional practice as well as an effective hook to frame complex, cross-disciplinary problems. This literature review shows growing support for incorporating bioinspired design concepts in undergraduate curricula and identifies some of the engineering programmes in the USA and internationally that are already incorporating bioinspired design courses into their curricula for students from the second- to third-year levels. While progress is being made in expanding existing engineering curricula to include bioinspired design concepts, little is known about how to teach bioinspired design or to support students in the discovery and knowledge transfer processes that enable design innovation to occur. There is still a need to establish instructional resources and best practices for teaching bioinspired design at the undergraduate level, which this research aims to address.

The C–K theory is used to create instructional resources (teaching module, C–K mapping template, learning activities, assignment), as it is known for integrating multiple domains of information and facilitating innovation through connection building. A C–K mapping template was created that visually structures the discovery and knowledge transfer process, and it was demonstrated that this template is an adaptable instructional resource that can facilitate the knowledge transfer processes of bioinspired design going from biology to engineering (biology-driven) as well as from engineering to biology (problem-driven). An accompanying set of guidelines for filling out the template was created to assist novice learners. The instructional resources were piloted in a second-year engineering design course that teaches the fundamentals of engineering design theory and methodology with a course project focused on designing an HPV. Qualitative content analysis of student reflection statements generated in this course revealed that the instructional resources resulted in significant learning of both biology and bioinspired design, as well as learning engagement and value of the experience.

The authors believe that this research will stimulate additional interest in this area and contribute to developing a database of evidence-based instructional resources, as well as new and effective teaching methods which will enhance the pedagogy of bioinspired design in the engineering curriculum. More generally, the authors believe that this research shows that teaching bioinspired design in an engineering curriculum can help to develop many of the competencies required of the twenty-first-century engineer as well as twenty-first-century skills that are essential to being successful in the global workforce and tackling the cross-disciplinary challenges that lie ahead.[45] Teaching bioinspired design offers the potential to train students not just to explore the biological domain for solutions, but also to have the cognitive flexibility, creativity and adaptive problem-solving skills for exploring any contextual domain from which they might find solutions to complex, cross-disciplinary engineering problems.

## Acknowledgements

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. This material is based on work supported by the National Science Foundation under Grant 1504612. The authors would like to thank the JMU engineering students that participated in the study.

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# Significance, Prevalence and Implications for Bio-Inspired Design Courses in the Undergraduate Engineering Curriculum

**Conference Paper** · August 2016

DOI: 10.1115/DETC2016-59661



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**Proceedings of the ASME 2015 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference**
**IDETC/CIE 2016**
**August 21-24, 2016, Charlotte, North Carolina, USA**

**DETC2016-59661**

# SIGNIFICANCE, PREVALENCE AND IMPLICATIONS FOR BIO-INSPIRED DESIGN COURSES IN THE UNDERGRADUATE ENGINEERING CURRICULUM

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## ABSTRACT

Engineers in the 21st century can no longer isolate themselves and must be prepared to work across disciplinary, cultural, political, and economic boundaries to meet challenges facing the US and the world. Recently, a greater emphasis is being placed on understanding social, economic and environmental impacts of engineered solutions. Undergraduate education must train students to not only solve engineering challenges that transcend disciplinary boundaries, but also communicate, transfer knowledge, and collaborate across technical and non-technical boundaries. One approach to achieving this goal is through introducing bio-inspired design in the engineering curriculum. Bio-inspired design encourages learning from nature to generate innovative designs for man-made technical challenges that are more economic, efficient and sustainable than ones conceived entirely from first principles. This paper reviews the literature pertaining to current approaches to teaching bio-inspired design in and engineering curriculum curriculum at different institutions as well as the essential competencies of the 21st century engineering. At James Madison University a Concept-Knowledge Theory instructional approach was adopted for teaching sophomore engineering design students bio-inspired design to foster many of the 21st century competencies. A pilot study was conducted to demonstrate that the 21st century competencies can be targeted and achieved. The results of study are presented, and the significance and implications of teaching bio-inspired design in an engineering curriculum are discussed.

## INTRODUCTION

Innovative engineering design tools and methods are essential to creating new and better products and industries, and are also important for the US to maintain and sustain its global economic leadership. "Design Quality" is the main factor that differentiates one competing product from another. Companies such as Toyota, Apple, and Samsung are pioneers in positioning design as a key contributor to innovation. "Design Innovation" has been identified as an important learning approach for students in science, technology, and engineering disciplines by national organizations, like the National Science Foundation and the National Academy of Engineering, among others.

Undergraduate engineering programs that focus exclusively on engineering principles throughout the curriculum will not be able to train students to recognize interrelationships or be adaptive problem solvers. The connections within engineering may be obvious to students, or students might take it for granted that some aspects are similar. With bio-inspired design, however, many of the connections to be made between biology and engineering will not be obvious and making these connections will require critical thinking and investigation from multiple system levels and viewpoints, thus emphasizing systems thinking.

The knowledge base in biology has proven to be a useful resource for engineers searching for novel or creative approaches for solving complex design problems. Biological systems provide insight into sustainable and adaptable design, which has been used to inspire engineering innovation. Bio-inspired designs (sometimes referred to as biomimicry or biomimetics) are viewed as creative and novel solutions to human problems and are often efficient, economic, elegant and sustainable. Moreover, some bio-inspired designs, such as Velcro, have become so commonplace that it is hard to image life without them. Other imitations of nature now on the cusp of practical usefulness, such as artificial photosynthesis, could lead to enormous societal benefits including regional energy independence and reduced greenhouse emissions. The overarching motivation is not just to train students to explore the biological domain for solutions, but to have the cognitive flexibility, creativity, and adaptive problem solving skills to explore any contextual domain from which they might find solutions to complex, cross-disciplinary engineering problems. Teaching students about bio-inspired design improves their cross-disciplinary thinking skill which is among the essential competencies outlined in the Engineer 2020 Report and other organizations and researchers as discussed in the section below.

 

## ESSENTIAL COMPETENCIES OF THE 21ST CENTURY ENGINEER

The Engineer 2020 report, ABET, and researchers have identified the essential competencies for engineers to be prepared to work across disciplinary, cultural, political, and economic boundaries to solve complex design challenges. Undergraduate education must train students to not only solve engineering challenges that transcend disciplinary boundaries, but also communicate, transfer knowledge, and collaborate across technical and non-technical boundaries. The competencies given below can be divided into two groups, task-specific and meta competencies. Task specific competencies are skill sets that defines how well-prepared graduates are to meet the workforce challenges that lie ahead based on their level of attainment [1]. Meta competencies are skill sets that enable graduates to function globally while meeting technical demands, have the cognitive flexibility to think about the whole system at different levels of fidelity and in different time scales, and transfer task-specific skills to new challenges or tasks they have not encountered before [2]. While not an exhaustive inventory of the literature on engineering competencies, the following lists outline the essential competencies for the 21st century engineer from three key perspectives.

**Competencies outlined in the Engineer 2020 report**

The Engineer 2020 report is an initiative by the National Academy of Engineering (NAE) to define the attributes required for an engineer in 2020 and actions that may be taken to promote achievement of these attributes. The vision states that engineering graduates [3]:

- will possess strong analytical skills, like engineers of yesterday and today
- will exhibit practical ingenuity
- will be creative
- will be good communicators
- will master the principles of good business and management
- will understand the principles of leadership and be able to practice these principles
- will have high ethical standards and a strong sense of professionalism
- will possess a complex attribute described as dynamism, agility, resilience, and flexibility
- will be life long learners.

**Competencies outlined by ABET**

The Accreditation Board for Engineering and Technology (ABET) holds engineering schools accountable for the knowledge, skills, and professional values that engineering students acquire in the course of their education. In order to do this, ABET established the following set of student outcomes that each program must demonstrate [4]:

- Outcome a: "an ability to apply knowledge of mathematics, science, and engineering"
- Outcome b: "an ability to design and conduct experiments, as well as to analyze and interpret data"
- Outcome c: "an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability"
- Outcome d: "an ability to function on multi-disciplinary teams"
- Outcome e: "an ability to identify, formulate, and solve engineering problems"
- Outcome f: "an understanding of professional and ethical responsibility"
- Outcome g: "an ability to communicate effectively"
- Outcome h: "the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context"
- Outcome i: "a recognition of the need for, and an ability to engage in life-long learning"
- Outcome j: "a knowledge of contemporary issues"
- Outcome k: "an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice"

**Competencies outlined in analysis to support engineering innovation**

Siddique et al. developed a competency-based approach to personalized education for 21st century engineers [5-8]. In their approach, the meta-competencies to support innovation were identified with acknowledgement that students will build on some competencies and add new ones as they progress through the curriculum. Built on a set of competencies complied by various educators and researchers, the following is a list of meta-competencies that need to be developed by future engineers to support innovation [6]:

Ability to Manage Information

- Ability to gather, interpret, validate and use information
- Understand and use quantitative and qualitative information
- Discard useless information

Ability to Manage Thinking

- Ability to identify and manage dilemmas associated with the realization of complex, sustainable, socio-techno-eco systems
- Ability to think across disciplines
- Holistic thinking
- Conceptual Thinking
- Ability to speculate and to identify research topics worthy of investigation
- Divergent and convergent thinking
- Ability to engage in critical discussion

- Identify and explore opportunities for developing breakthrough products, systems or services
- Ability to think strategically by using both theory and methods

Manage Collaboration
- Ability to manage the collaboration process in local and global settings
- Ability to create new knowledge collaboratively in a diverse team
- Competence in negotiation
- Teamwork competence

Manage Learning
- Ability to identify the competencies and meta-competencies needed to develop to be successful at creating value in a culturally diverse, distributed engineering world
- Ability to self-instruct and self-monitor learning
- Ability to interact with multiple modes of learning

Manage Attitude
- Ability to self-motivate
- Ability to cope with chaos
- Ability to identify and acknowledge mistakes and unproductive paths
- Ability to assess and manage risk taking

Comparison and synthesis of the different perspectives on competencies for the 21st century engineer reveals the following common themes.

- Holistic, Critical thinking
- Complex, Multidisciplinary problem solving
- Creativity
- Communication across disciplines
- Understand impact in global, economic, environmental, and societal contexts
- Collaboration in a multidisciplinary team
- Self-regulated learning
- Flexibility and agility
- Global Awareness

Students learning through bio-inspired design have the potential to meet all of these competencies. Bio-inspired design is inherently interdisciplinary and blends information from biology, engineering, physics, mathematics, architecture, and design and consequently fosters the first four competencies. With communication also including scientific literacy [9]. Understanding impact is fostered through comparing natural to engineered solutions and recognizing that all materials, forms, and processes of natural systems have a purpose (a function) and sometimes multiple purposes as well as projects that require designing for those outcomes. Bringing together teams of people across disciplinary boundaries, within and outside engineering, fosters innovation through the diversity of thought and communication. While inter-professional teams are the strongest, there maybe institutional limitations that prevent such teams. Learning, flexibility, and agility are fostered through open-ended questions and projects that require the student to define the problem and inspiring biological system. The final competency can be fostered through considering the biological systems in regional areas across the globe or working with teams abroad.

In the current context, it is widely recognized that most students that go into engineering have high school level training in biology. Adding biomimicry into the engineering curriculum encourages students to utilize and build off their prior knowledge, which fosters making connections and recognizing interrelationships across STEM disciplines[10, 11]. Moreover, requiring knowledge transfer across domains as well as organizing that knowledge into logical constructs helps to develop future flexibility and adaptive expertise that will facilitate innovation and efficiency[12, 13]. These competencies have also been identified as critical key skill areas for engineers by the Partnership for 21st Century Skills [14] and the Assessment and Teaching of 21st Century Skills working group [15]. Instruction on bio-inspired design concepts will help engineering colleges achieve a number of the recommendations made by the National Academy of Engineering in reference to educating the engineer of 2020 [3], as well as ABET student outcomes c, d, e and h [4] and foster competencies that support engineering innovation.

## TEACHING BIO-INSPIRED DESIGN

In response to the increased emphasis on cross-disciplinary thinking skills and adaptive and sustainable designs by professional societies, industry and today's global marketplace, engineering colleges in the United States and abroad are increasingly expanding the scope and focus of their curricula to include bio-inspired design topics and projects that expand systems thinking skills, and has been integrated at the module, project, or course levels [10, 11, 16-29]. While instruction in bio-inspired design is quite common in engineering programs at the graduate level, it is exciting to note that bio-inspired design instruction is also being incorporated into curricula at the undergraduate level as described in Table 1. It is important to note that this list is not meant to be exhaustive but rather to emphasize that it is feasible to creatively integrate bio-inspired design into the undergraduate curriculum from the sophomore to senior levels. The following sub-sections detail how bio-inspired design instruction has been integrated into undergraduate engineering curricula.

### Courses in Bio-inspired Design

Several institutions including Georgia Tech (Center for Bio-inspired Design), Arizona State University, Northern Arizona University [30], University of St. Thomas [31], Duke University, University of Delaware, and others have been engaging in innovative research and developing educational materials (environmental ethics, course for artists, etc.) related to

biomimicry. The instructional resources and activities need to be tailed for systematic use in courses such as design and simulations in engineering as well as non-engineering disciplines. The Biomimicry Institute (www.biomimicryinstitute.org) and teachEngineering.org are also promoting biomimicry concepts by giving workshops and training to academic faculty and K-12 teachers.

Multiple institutions offer semester long engineering courses in bio-inspired design or interdisciplinary courses that bring together students from STEM and art. Probably the most well known institution is Georgia Tech, which offers multiple courses and a certificate through the Center for Bio-inspired Design [32-34]. The undergraduate interdisciplinary course is co-taught by faculty from biology and engineering, and admits junior and senior level students from all fields of engineering and biology. Two processes for bio-inspired design, problem-driven and solution-driven, are taught in the course, and analogies are formed through functional decomposition similarly to functional modeling in engineering design [33]. More recently, the four-box method that identifies function, operating environment, constraints, and performance criteria as dimensions for matching biological analogues with the design problem has been implemented [35]. Students work in interdisciplinary teams on assignments and projects throughout the course. Honors-level undergraduate courses similar to the one at Georgia Tech have been offered at institutions such as Virginia Tech.

The mechanical engineering department at Montana State University offers a senior level technical elective on bio-inspired engineering [26]. The course covers relevant bio-inspired design and engineering design processes with a focus on structures and materials from both nature and engineering. The practices taught in the course include reverse engineering and tabulating a variety of relationships. Thus, the focus is more on comparison than innovation. Texas A&M is currently developing an undergraduate course to introduce interdisciplinary engineering students to multiple methods of bio-inspired design [22]. The course will be an elective in the mechanical engineering curriculum that focuses on breath of approach rather than depth, exposing students to the state-of-the-art in bio-inspired design research tools and methods. At the Olin College of Engineering, all students take a course that introduces bio-inspired design in their first semester. The course is called Design Nature and is an introduction to the engineering design process that also weaves in concepts from nature. Students complete individual and team projects in the course. Similarly, all first year engineering students at the University of Calgary are introduced to biomimicry in their design and communication course.

At Kettering University, in the Industrial and Manufacturing Department, biomimicry is integrated into an ergonomics course through problem-based learning [19]. Students work individually on projects using the Biomimicry Innovation Tool, which blends aspects of problem based learning, innovation, biomimicry, and ergonomics into a single student experience. They present their bio-inspired concept at the end of the course. The University of Maryland offers a course in biomimetic robotics as a senior elective in the mechanical engineering program [17]. Students study biological locomotion and how it can inspire efficient mechanisms of motion.

It is evident from reviewing the Bio-inspired Design course offerings at various institutions listed in Table 1 either as electives or regular courses, students are being exposed to 21st century competencies, specifically related to collaboration and creativity and innovative solutions to open-ended design problems. In order to systematically evaluate all of the 21$^{st}$ century competencies in various courses at different institutions, a more rigorous approach to surveying the students is required.

**Bio-inspired Design Modules and Projects**

Bio-inspired design concepts and examples have been used by several institutions to educate students on design innovation and as another source of design inspiration. Institutions include Oregon State University, University of Georgia, James Madison University, Purdue University, Clemson University, Penn State University-Erie, University of Maryland, Indian Institute of Science, University of Toronto and Ecole Centrale Paris to name a few. Often the instruction is across less than four lectures, which reduces the burden of integration into existing courses. These institutions also require engineering students to complete assignments or a project involving bio-inspired design to practice the technique and demonstrate its value. Integration occurs at the freshman through senior levels, in a variety of departments, and primarily depends on when engineering design is offered in the curriculum. Consequently, varying levels of instruction and support are provided to the students, and many rely on the resources provided by the Biomimicry Institute, such as the database AskNature.org. This points to the lack of engineering-focused, evidence-based instructional resources available to faculty that wish to integrate bio-inspired design into their courses.

## OBERVATIONS ON THE STATUS OF BIO-INSPIRED DESIGN COURSES IN UNDERGRADUATE ENGINEERING CURRICULA

As can be seen from the discussion presented in the previous section, it is interesting that universities and institutions within the United States and aboard are beginning to recognize that it is important to expand undergraduate engineering curricula and are offering courses, modules and project based learning activities with an emphasis on bio-inspired design thinking. Implementing biomimicry concepts into engineering design curriculum presents a unique opportunity to incorporate fundamental curiosity driven and technology perspectives and involve collaborations from multiple disciplines. In addition, faculty from various disciplines will have the opportunity to engage in a collaborative teaching environment and share valuable experiences and insights. Moreover, anecdotal evidence suggests that students find bio-inspired design exciting, as it offers relevance to professional practice as well as an effective hook to frame complex, cross-disciplinary problems. As an example, one of the student groups in a sophomore design course at the University of Georgia, took inspiration from the

*Table 1. A sampling of bio-inspired courses at US Universities and Abroad*

| University | Institute/ Department | Course Level | Emphasis |
|---|---|---|---|
| **United States Institutions** | | | |
| Georgia Tech | Center for Bio-inspired Design | Junior and Senior level students in engineering and biology | Problem driven and solution driven approaches to bio-inspired design; four box method for matching biological analogies to design problems |
| Virginia Tech | Industrial Design | Honors undergraduate engineering students | Problem driven and solution driven approaches to bio-inspired design; Biomimicry principles, concepts, and methodologies |
| Montana State University | Mechanical Engineering | Technical Elective for Seniors | Comparison of structure and materials from nature and engineering |
| Kettering University | Industrial and Manufacturing Dept. | Senior Level | Biomimicry concepts integrated into an ergonomics course; use Biomimicry Innovation Tool |
| University of Maryland | Mechanical Engineering | Elective for seniors | Biological locomotion as an inspiration for designing efficient mechanisms for motion |
| Olin College of Engineering | College of Advancing and Professional Studies | Required course for first year students | Design process using biomimicry principles, concepts, and methodologies |
| Texas A & M University | Mechanical Engineering | Elective for seniors | Research methods and tools for bio-inspired designs |
| **International Institutions** | | | |
| University of Calgary | Schulich School of Engineering | First year common core course | Design using natural proportions (the golden selection) and biomimicry as a design approach |
| Imperial College London | Mechanical Engineering | Elective for seniors | Structural analysis of forms from nature and engineering |

Namibian beetle, specifically in regards to how it harvests moisture from the air by first getting it to condensate on its back and storing it, and designed a system to collect water using metal sheets and tubing for filling dog bowls or watering crops. Courses incorporating bio-inspired design into engineering curricula, might help students to think innovatively in a multidisciplinary fashion. Another advantage to including bio-inspired design courses in undergraduate engineering curricula is that bio-inspired design touches on many areas of engineering including electrical, mechanical, materials, biomedical, chemical, manufacturing and systems, which makes it applicable in a wide range of engineering programs, from discipline specific to general ones. Thus, there are several opportunities to foster the nine distilled competencies of 21$^{st}$ century engineers in a variety of institutional settings through bio-inspired design with engineering design courses being the most advantageous. Many of the current offerings are at the senior level, which provides the advantages of students being able to apply complex engineering theories, work efficiently in teams, communicate well, perform research, and think abstractly and holistically. It is expected that students are meeting the ABET outcomes by their senior year, which can allow for a richer course experience, but may not carry over into their professional work. On the other hand, introductory level courses in the first year expose students to a new way of thinking that could be reinforced throughout their college coursework thus embedding the approach in their problem solving process and will foster some of the nine distilled competencies. Ideally, students would apply bio-inspired design throughout an engineering curriculum to ensure the competencies are met.

Finally, the authors believe that teaching multidisciplinary design through biomimicry will be vital to promoting future innovation in engineering design and will also attract women and minority students with diverse backgrounds to pursue science and engineering fields. Curricula that are more practically and socially relevant, such as focusing on skill development related to engineering practice, have shown to attract more women and minorities [36-39].

While bio-inspired design is rapidly gaining in popularity in engineering courses, little is known about how to teach it or support students in the discovery and knowledge transfer processes that enable design innovation to occur. There are now more calls for research identifying and establishing best practices for teaching bio-inspired design concepts at the undergraduate level. We are currently using support from the National Science Foundation to develop instructional resources that can help to effectively scaffold students to transfer knowledge across disciplinary boundaries and train engineers in cross-disciplinary thinking. We propose to use Concept-Knowledge (C-K) Theory [40-43] in developing instructional resources, as it is a well-established approach for integrating multiple domains of information and facilitating innovation through connection building. The instructional resources are designed to foster the competencies of holistic, critical thinking; complex, multidisciplinary problem solving; creativity; communication across disciplines; understand impact in global, economic, envi-

ronmental, and societal contexts; self-regulated learning; and flexibility and agility. Through the design, implementation, and evaluation of our instructional resources for bio-inspired design, we will not only create evidence-based resources, but also discover new and effective teaching methods, which will enhance the pedagogy of bio-inspired design in an engineering curriculum.

## BIO-INSPIRED DESIGN PILOT STUDY AT JAMES MADISON UNIVERSTIY

During a pilot study at James Madison University, the C-K theory instructional approach was adopted for teaching a sophomore engineering design class to specifically address how the 21st century competencies can be targeted and achieved.

### Pilot Study Approach

To implement the C-K theory instructional approach a bio-inspired design teaching module, learning activity, and assignment that incorporated a C-K mapping template with guidelines was created and integrated into the course during the topic of concept generation and introduced as a creative method for design. All assignments in the sophomore design course tie to a year-long course project of developing a human powered vehicle for a client in the community that has cerebral palsy, including the bio-inspired design assignment. To integrate bio-inspired design into the human powered vehicle design project each member of a team applied bio-inspired design to a different sub-system (e.g., propulsion, steering, braking) of their design to showcase a variety of design problems and analogies that enable bio-inspired design. All students completed the C-K mapping template three times, twice in class as part of a learning activity to understand the process of discovery and again in their assignment to scaffold application to the human powered vehicle.

The developed teaching module introduces bio-inspired design as a design philosophy and provides several examples of how biological systems were used as inspiration for innovative solutions. Students learn about the two major paths to a bio-inspired de-sign, biology-driven and problem-driven, as well as how analogies are used to assist with transferring the knowledge from biology to engineering. For the purposes of scaffolding the sophomore engineering de-sign students in their application of bio-inspired de-sign, two problem-driven examples using C-K theory were provided with accompanying learning activities. One problem-driven example and learning activity focused on the hingeless facade shading mechanism, Flectofin®, inspired by the bird-of-paradise flower [44]. Shading buildings with irregular geometries is very difficult since most sun protection systems were developed for planar façades and include the use of hinges. The pollination mechanism of the bird-of-paradise flower offers inspiration based on the elastic kinematics of plant movements. After the initial problem is explained, students are provided the partially filled in template shown in Figure 1 to complete during the explanation of the example. This scaffolds the students through the C-K theory mapping process. Students are walked through the thought processes and analogies of the discovery process for arriving at a bio-inspired solution using the C-K theory framework.

The developed assignment that compliments the teaching module and learning activities includes three parts: 1) complete the C-K mapping template for a human powered vehicle subsystem, 2) use the sketches in the C3 level of the template along with the team generated morphological matrix to create a full human powered vehicle concept, and 3) a W/H/W re-flection essay answering three questions about the content and process. The W/H/W reflections require learners to reflect on and respond to three questions: What did I learn?, How did I learn it?, and What will I do with it? These three prompts structure reflection so that learners focus on concepts, knowledge and skills, processes, and utilization/generalization/sustaining of learning. The W/H/W reflections provide formative snap-shots of learning and application that the learners are making as they progress through the material.

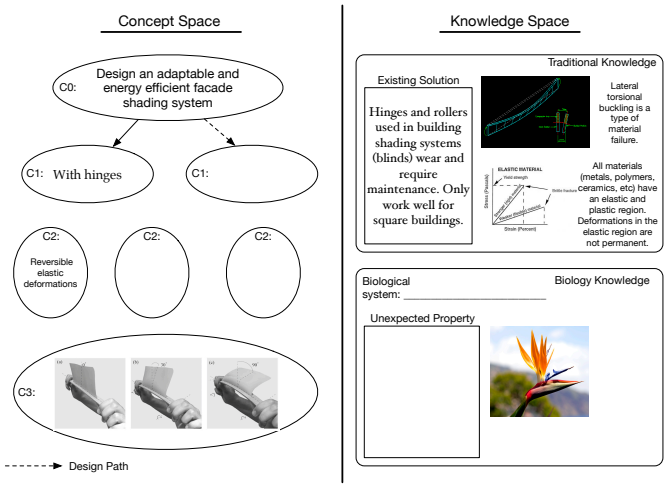


***Figure 1: Template for Hingeless Facade Shading Mechanism Learning Activity***

### Pilot Study Analysis

Analysis of the W/H/W reflection questions aims to identify which 21st century competencies were achieved by incorporating bio-inspired design education in an engineering design course. Fifteen (65%) students consented to participate in the research. Transcriptions of the reflection questions for consenting participants were de-identified and analyzed using qualitative content analysis. Qualitative content analysis identifies themes in the student reflections. This method involves reducing participants' comments to their smallest meaningful unit, coding these units, identifying categories for these codes, and then finally identifying themes from the categories [45]. The reflection statements resulted in 206 (108 for content questions and 98 for process questions) unique/coded meaningful units. Multiple themes and categories emerged for each question based on coded meaningful units. Themes for each reflection question including the number of student responses that support that theme, and the distilled competencies that the instructional resources were intended to foster are given in Table 2.

*Table 2. Mapping of Reflection Questions to Themes and Competencies*

| Reflection Question | Themes (n = supportive categories) | Competencies Addressed |
|---|---|---|
| What did I learn about the content? | • Valued what can be learned from nature and biology (17)<br>• In-depth understanding of chosen biological system (14)<br>• Cross-domain linkages (11)<br>• Biology is not always applicable (4) | • holistic, critical thinking<br>• self-regulated learning<br>• communication across disciplines |
| How did I learn the content? | • Scholarly or external resources (31)<br>• Course learning resources (4) | • self-regulated learning<br>• communication across disciplines |
| What am I going to do with the content? | • Apply to immediate problem – course project (16)<br>• Facilitate a future design path (11) | • flexibility and agility<br>• complex, multidisciplinary problem solving<br>• creativity |
| What did I learn about the process? | • Valued the inclusion of biology in engineering design (22)<br>• Recognized knowledge transfer between domains for problem solving is possible (17)<br>• Bio-inspired design is not always applicable (3) | • holistic, critical thinking<br>• communication across disciplines<br>• understand impact in global, economic, environmental, and societal contexts |
| How did I learn the process? | • Course learning resources (20)<br>• External or other resources (13) | • self-regulated learning<br>• communication across disciplines |
| What am I going to do with the process? | • Facilitate a future design path (20)<br>• Apply to immediate problem – course project (3) | • flexibility and agility<br>• complex, multidisciplinary problem solving<br>• creativity |

Focusing on the content (biology knowledge), students learned that biological systems are surprising complex but have attributes that can easily be applied to design problems. Recognition that nature has a lot to offer resulted in valuing what can be learned from biological systems. Conversely, a few students concluded that biological knowledge is not always applicable to the design problem. Both of these themes as well as forming cross-domain linkages link to the competency of critical thinking as students had to analyze the information they were finding and manage their own thinking about the information. The competencies of self-regulated learning and communication across disciplines link strongly to the themes of students learning about biological systems by engaging with scholarly resources through independent research, and forming cross-domain linkages as students had to dive deeper into the literature than just looking at the pictures to understand how the biological system relates to their chosen problem. Similar trends were observed for what students learned about the process of bio-inspired design. Critical thinking was exhibited in recognizing the value (or not) of including biological inspiration in a design process and that the process facilitates knowledge transfer between the domains that results in solutions to engineering problems. Communication across the disciplines is also evident in the recognition of knowledge transfer across domains. Understanding impact in a broader context was evident as looking to nature for inspiration resulted in students finding possible solutions that they thought were more sustainable than the existing engineering solution.

The competencies of self-regulated learning and communication across disciplines directly relates to how students learned the content and process. In both cases, internal resources (the instructional materials) and external resources (scholarly works and websites) were used to learn the content and process. It is not surprising that external resources were heavily used for learning the biology knowledge as it was required for students to identify and learn about the inspiring biological system independently. Whereas all the resources for learning the process were modeled in class and provided for the assignment.

With respect to what the students are going to do with the content and process it was not surprising to see the main trends of application to the course project and future opportunities. Creativity as well as flexibility and agility are expressed in the application of the analogically distant information (biology) to the target problem in engineering, and generally gaining a new perspective when designing. The competency of complex, multidisciplinary problem solving is embedded in the application of bio-inspired design to a specified problem, and it is encouraging to see the trend of wanting to use bio-inspired design when designing or solving engineering and non-engineering problems in the future.

One student expressed that learning about biology helped in gaining further knowledge about a specific sub-system of the human powered vehicle. Similarly, two students expressed that they would use existing biology knowledge to help understand engineered components and systems. Meaning, the students learned more about engineering through biology. This unanticipated result points toward the significance of teaching bio-inspired design in an engineering curriculum. Teaching bio-inspired design in an engineering curriculum using interdisciplinary approaches will not only develop competencies of the 21st century engineer but also enable undergraduate students to become change agents and promote a sustainable future.

**Pilot Study Limitations and Future Work**

Limitations to this pilot study include the low sample size, implementation at a single institution, and the use of student self reported data. To increase sample size numbers all sections of the JMU sophomore engineering design course will be asked to participate in the study. Grouping qualitative data from the six student reflection question statements to create themes was challenging as some responses seemed to be for a different question. Future work also includes implementation plans for the C-K Theory instructional materials in a sophomore engineering design course at the University of Georgia. Through the creation of rubrics for analysis of the student generated artifacts (C-K mapping template and concept) comparison of student work across institutions will be possible, and it will provide an objective measure to judge transferability of instructional materials from JMU to UGA, or visa versa.

## CLOSING REMARKS

It is well known that engineering involves integrating broad knowledge towards some purpose, generally to address a need or solve a problem. As we move into a global future, undergraduate education will need to prepare engineers to work in multidisciplinary, interdisciplinary, and transdisciplinary environments [46]. Undergraduate education must train students to not only solve engineering challenges that transcend disciplinary boundaries, but also communicate, transfer knowledge, and collaborate across technical and non-technical boundaries. One approach to achieving this goal is teaching biomimicry or bio-inspired design in the engineering curriculum [47]. Cross-disciplinary instruction in biomimicry will increase engineering students' cognitive flexibility, creativity, and adaptive problem solving skills. Biomimicry also touches on many areas of engineering including electrical, mechanical, materials, biomedical, chemical, manufacturing and systems, which makes it applicable in a wide range of engineering programs, from discipline-specific to general ones.

Teaching bio-inspired design in an engineering curriculum meets many of the competencies of the 21st century engineer, which are vital as we move into a global future. We demonstrated through a pilot study that many of the essential competencies such as thinking critically and making judgments; solving complex, multidisciplinary open-ended problems; communicating and collaborating across disciplines; making use of knowledge and information in creative ways; engaging in lifelong learning; and transferring problem solving skills across a variety of problems and contexts can be fostered in an engineering curriculum through bio-inspired design. We believe these are transferrable skills that will enable future engineers to be successful in the global workforce and help them tackle the cross-disciplinary challenges that lie ahead. Furthermore, teaching engineers bio-inspired design has the possibility to not just train students to explore the biological domain for solutions, but to have the cognitive flexibility, creativity, and adaptive problem solving skills to explore any contextual domain from which they might find solutions to complex, cross-disciplinary engineering problems.

We reviewed the literature to show growing support for incorporating bio-inspired design concepts in the undergraduate curriculum and presented some of the engineering programs in the United States and abroad that are already incorporating bio-inspired design courses into their curricula for students from the sophomore to junior levels. While progress is being made in expanding existing engineering curricula to include bio-inspired design concepts, there is still a need to establish best practices for teaching bio-inspired design at the undergraduate level. It is our belief that this research will stimulate additional interest in this area and contribute to developing a database of evidence-based instructional resources, as well as new and effective teaching methods, which will enhance the pedagogy of bio-inspired design in the engineering curriculum.

## ACKNOWLEDGEMENTS

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. This material is based upon work supported by the National Science Foundation under Grant No. 1504612.

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APRIL 2016
VOLUME 19 / ISSUE 1

# Systematic Bio-inspired Design: How Far Along Are We?

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■ **ABSTRACT**

Biological organisms, phenomena, and strategies provide insight into sustainable and adaptable design—which, in turn, can inspire engineering innovation. The majority of inspiration taken from Nature to date, however, has happened by chance observation (such as VELCRO®), or through dedicated study of a specific biological entity (such as the gecko). This historical state reveals a fundamental problem of working across domains (biology and engineering in this case) and begs the question: "Is a systematic approach to bio-inspired design (BID) possible?" Taking a systematic approach to BID could remove the element of chance, reduce the amount of time and effort required to develop bio-inspired solutions, and make the biological information accessible to engineering designers with varying biological knowledge, but a common understanding of engineering methodologies. This paper provides a perspective on achieving systematic BID—and on the progress made toward this goal.

## WHAT IS SYSTEMATIC BIO-INSPIRED DESIGN?

*Bio-inspired design* (*BID*) is the act of studying Nature to solve human problems. It can lead to the discovery of innovative or non-conventional problem solutions that are often more efficient, economic, and elegant. *Systematic BID* is following a process that routinely and appropriately considers Nature, and uses the kinds of processes, methods, and tools that facilitate access to–and use of–Nature's solutions and data that are potentially relevant to the problem at hand. Rather than relying solely on chance, ways to trigger and expedite the 'eureka' moment of inspiration are embedded in the process.

## WHERE CAN WE/SHOULD WE BE SYSTEMATIC?

Some consider BID to fit best in the systems engineering lifecycle during conceptual design and preliminary design tasks (Figure 1). It is during these tasks that engineers identify alternative design concepts and approaches, and accomplish trade studies. However, we must not limit our thinking to the idea that BID approaches are applicable in only a few places in the systems engineering lifecycle. Once an engineer identifies an inspiration source in Nature and chooses a basic solution approach, one may often have to dig deeper to understand the biology and learn from it. This might occur during detailed analysis and development tasks.

Systems engineering as well as engineering design are process driven disciplines (not physical law driven sciences such as physics). Innovation in engineering problem solving is heavily reliant on the engineer or engineering team. First, the team must be able to distinguish the critical features of the problem at hand. Second, the team needs to be adept at the using available processes, methods, and tools to derive viable solutions. Third, the team must recognize that each project is different. Having a clear understanding of the problem and trusting the process helps to ensure that the chosen solution will satisfy the requirements. If BID is to be systematic, the processes, methods, and tools must support timely, appropriate, and efficient consideration of Nature as a source of inspiration.

BID involves working with biological information at different levels, such as identification of inspiring systems, translation of biological information to the problem at hand, and application of Nature-based inspiration to create useful solutions. Because the act of taking inspiration from Nature is a *process* rather than a single step, I believe the BID process can be *systematic*, just like the systems engineering and engineering design processes are systematic. That is, the goal is to use a structured plan or process. While not everything can be captured in a systematic process, the methods and tools that one would use can enable the spontaneous and creative insights to occur. Knowledge transfer is not a systematic activity, but rather an ability to extract themes and principles from information, which, in turn, supports the transfer of information. Methodically studying the characteristics and behaviors of an inspiring biological organism aids with

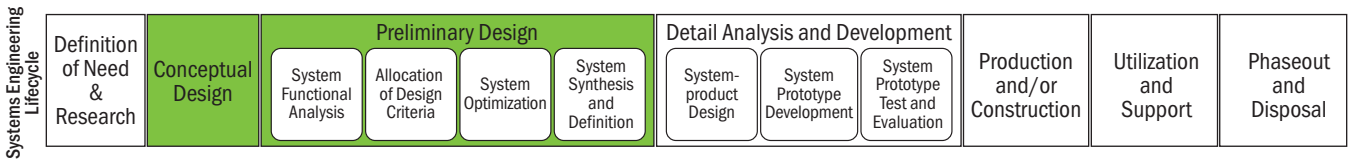


*Figure 1. Some perceive BID to fit best with the early (highlighted) stages of the systems engineering lifecycle (adapted from Blanchard and Fabrycky 1998)*

understanding the organism—and how such knowledge might assist with solving the problems and challenges occurring during a specific system development effort. The BID aspects of the systems engineering process can be more systematic and repeatable than they have been in the past.

Although there is great potential for engineers to learn from Nature as they design and develop systems, there exists a disconnect in *how* engineers go about considering Nature's ingenuity. To date, bio-inspired designs have usually been more of a novelty, rather than resulting from a well-defined, systematic process. The majority of bio-inspired design has happened by chance observation (such as VELCRO®) or by dedicated study of a specific biological organism (such as the gecko). This historical state makes BID seem unachievable unless: a) there is a serendipitous eureka moment, or b) a significant amount of time and effort is devoted to the task.

This reveals a fundamental problem of working across domains. The effort and time required to become a competent engineer creates significant obstacles to also becoming sufficiently knowledgeable about biological systems. The converse is also true. This, in turn, motivates the need for BID facilitating method and tool development, as well as motivating process approaches that enable rapid, efficient interdisciplinary communication and collaboration among engineers and biologists.

## WHAT PROGRESS HAS BEEN MADE?

It is increasingly evident that Nature ***can*** inspire innovative engineering solutions and offer insight on new product or system opportunities. For engineers to achieve systematic BID practices, however, the engineering community needs both tools that facilitate BID and guidance on how those tools support the process. Figure 2 graphically depicts the progress made toward achieving systematic BID. This progress has been accomplished primarily by researchers in academia, with some of these researchers having ties to industry. Methods and tools that facilitate the BID process include keyword searches, reverse engineering, functional modeling, and use of databases. These BID facilitators reduce the time and effort required to learn from and mimic Nature.

Sarkar et al (2008) developed a software package entitled Idea-Inspire to support generation of solutions for product design problems. Their method provides a search method using a verb-noun-adjective set that enables analogical reasoning at different levels of abstraction. The database is comprised of biological and engineered mechanical systems. Similarly, the DANE (Design by Analogy to Nature Engine) software developed by Vattam et al (2010) provides access to a design case library containing Structure-Behavior-Function (SBF) models of biological and engineering systems (Hoeller 2013). Users may search and access systems through a functional representation embedded in both libraries—with search results presented to users in various multi-media forms. Both approaches seek to inspire ideas, rather than to solve the problem directly.

Wilson and Rosen (2007) explored reverse engineering of biological organisms for knowledge transfer. To do this, engineers must abstract or decompose the biological organisms into physical and functional parts, with a behavioral model and truth table depicting system functionality. This then allows the designer to describe the biological organism with domain-independent terms to allow for the transfer of general design principles. Vincent and Mann (2002) developed a method that focuses on technology transfer between biology and engineering domains named BioTRIZ (meaning a bionics version of the Russian-developed tool derived from patterns found in patent literature 'the theory of inventive problem solving' (www.bio-triz.com)). By reformatting the problem into a contradiction, a list of biological systems that have addressed that contradiction are generated. This, in turn, leads the designer to specific sources of biological inspiration. The designer then utilizes the presented sources to develop a solution concept. Chiu and Shu (2007) have developed a method for identifying relevant biological inspiration by searching available biological knowledge in a natural-language format using functional keywords. Engineering keywords are used to explore WordNet to create a set of natural-language keywords that are more likely to be used in biology texts. This approach has been shown to improve inspiration-related search results.

The Biomimicry Institute provides a design methodology that challenges one to consider life principles and essential elements that promote the sustainability of natural designs (The Biomimicry Institute). This methodology includes an online database called AskNature (AskNature.org) that stores biological organism characteristics along with information on some of the bio-inspired designs based on these characteristics. [An introduction to this database is in the Hooker and Smith article in this *INSIGHT* issue.]

Nagel et al. (2013) developed a comprehensive design approach, including a methodology and supporting tools (search tool, biological functional modeling method, and engineering-to-biology thesaurus) that integrate with function-based design techniques to facilitate BID. Function-based design encompasses the methods and tools that explore the design space (set of all possible design solutions) in a

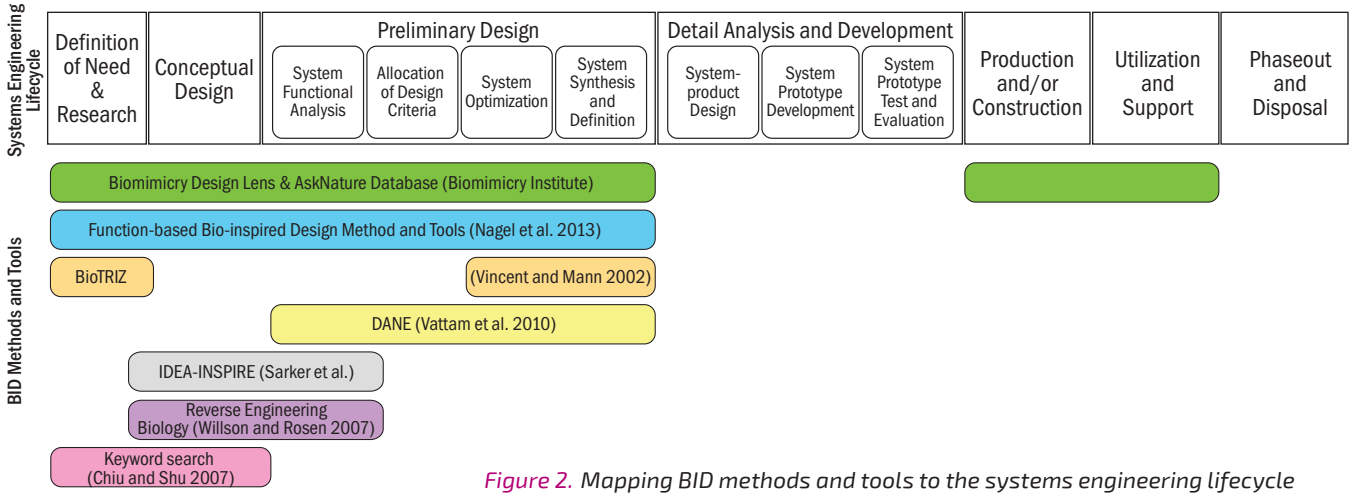


*Figure 2. Mapping BID methods and tools to the systems engineering lifecycle (adapted from (Blanchard and Fabrycky 1998) reveals development opportunities*

solution-neutral manner. The focus is on what a product or device must do, not *how* it will do it, thus the approach tends to rely on abstract representations. The function-based methodology supports two different starting, or perhaps motivating, points: a customer need motivated product design or a biological system motivated product opportunity. It has been demonstrated that this method presents the natural designs in an engineering context–which, in turn, assists with identifying the parallels that exist between engineering and biology and developing the analogies necessary between the two domains to inspire novel engineering solutions. Thus, biological information is more easily accessible to designers with varying biological knowledge.

The consultant community, such as Biomimicry 3.8, aims to be a catalyst to bring teams of the right people together to facilitate BID, while academia has focused on creating knowledge through evidence-based research. Biomimicry start-ups that are nimble and opportunity driven leverage information from academia and the consultant community to create bio-inspired products and processes. Industry at large, however, tends to be requirements driven and often has many problems yet to be solved. While BID research increases within industry, as demonstrated by patents with biomimetic content increasing faster as a proportion of total patents (Bonser 2006), we have yet to see BID as a common engineering practice. Industry as a whole has been generally slow to adopt BID approaches likely due to resource and organizational constraints. From this, we can conclude that there are many opportunities for future work and exploration.

## WHAT REMAINS TO BE DONE?

The engineering community has not reached systematic BID. Many efforts toward enabling systematic BID are occurring, but these: a) focus on different aspects of the process, b) do not yet interface together, and c) are not openly accessible to practitioners. More people are beginning to recognize BID as a viable problem-solving lens. There is genuine and slowly increasing interest from industry to apply it. However, those who champion BID need to do more work to facilitate widespread adoption. Table 1 provides a summary of current progress and opportunities for future work to enable more systematic BID.

Mimicking Nature means more than copying easily observed physical characteristics. Innovatively using Nature's inspirations relies heavily on the ability of the designer to make connections between dissimilar domain information, such as, biology and engineering. Creation of the processes, methods, and tools that facilitate making these types of connections would be advantageous. Working toward a broader mapping of BID concepts to the systems engineering lifecycle could reduce the creative leap to a set of more structured and manageable steps. Collectively, these can help practitioners adopt more systematic BID processes, and can make the concept of systematic BID more accessible and practical to the engineering community.

## CLOSING REMARKS

Although we have not yet reached systematic BID, progress continues. The broader impacts and benefits of systematic BID can serve as a great motivator. Systematic BID has the potential to:

- Alleviate the knowledge gap, assist with transferring valuable biological knowledge to the field of engineering
- Remove the element of chance, and/or reduce the amount of time and effort required to developing bio-inspired solutions
- Bridge the seemingly immense disconnect between the engineering and biological domains.

The creation of processes, methods, and tools that assist engineers with a limited biological background to *intentionally* generate BIDs, as opposed to relying upon chance exposures, has the potential to make a significant impact on society—by facilitating the discovery of less obvious strategic and sustainable solutions to complex problems. Systems engineers are well positioned to establish systematic BID and effectively move it into the practical technical domain of engineering by identifying how the various BID processes, methods, and tools can combine across the systems engineering lifecycle. ■

*Table 1: A comparison of progress made and what would be advantageous to enable systematic BID indicates potential areas for further process, method, and tool development*

| Progress To Date | Advantageous Goals |
|---|---|
| Keyword searching for biological inspiration in a database using a taxonomy of function | Search algorithms that perform automatic translation through identification of the biological agent involved in performing the functional keyword and mapping the language of biologists that describes the underlying causal mechanism to an engineering lexicon for function, physical principles, and solution archetype |
| Modeling biological systems with qualitative function or physical states to present the natural designs in an engineering context | Modeling using relational mappings that investigate the connections between physical and non-physical characteristics for gaining a deeper understanding of Natural ingenuity |
| Biology-driven or opportunity-driven approach—discovering an interesting biological characteristic and then seeking out ways to apply that new knowledge in a product or process | Problem-driven or requirements-driven approach—understanding the characteristics of problems that would benefit from applying BID |
| Valuing interdisciplinary teaming of biologists, engineers, and designers | Policies that require interdisciplinary teaming of biologists, engineers, and designers |
| A thesaurus that translates between the languages of biologists and engineers for terms of function and flow (Nagel 2012) | Common taxonomy to address communication issues among the broader communities of biologists, engineers, and designers |

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## ABOUT THE AUTHOR

Dr. Jacquelyn K.S. Nagel is an Assistant Professor of Engineering at James Madison University in Virginia, US. She has seven years of diversified engineering design experience, both in academia and industry, and has experience across a range of design contexts, including: BID, electrical and control system design, manufacturing system design, and design for the factory floor. Dr. Nagel teaches biomimicry in the context of engineering design, and her research focuses on pedagogy and applications of BID, as well as the development of methods and tools that facilitate the process. She earned her Ph.D. from Oregon State University, and her M.S. and B.S. from Missouri University of Science & Technology. In 2012, she was recognized by the National eWeek Foundation and IEEE-USA as one of the New Faces of Engineering for her pioneering work in using biological systems as models for sensors, instrumentation, and processes.

## Brown, CHRISTOPHER

Brown earned his PhD at the University of Vermont in 1983 studying chip formation in machining. The next four years were in the Materials Department at the Swiss Federal Institute of Technology studying surfaces. For two years, he was at Atlas Copco's European research center. Since 1989 Chris has been on the faculty at Worcester Polytechnic Institute. He has published over a hundred articles on machining, axiomatic design, sports engineering, and surface metrology. He has patents on surface roughness characterization, an apparatus for friction testing, and on sports equipment. He teaches courses on axiomatic design, surface metrology, manufacturing, and on the technology of alpine skiing. He also consults and teaches short courses for industry.

### Title of the Presentation:

Axiomatic Design for Creativity, Sustainability, and Industry 4.0

### Synopsis:

In this tutorial principles of Axiomatic Design (AD), including Suh's axioms and their application to design processes will be briefly reviewed. Then we will discuss how to foster creativity and sustainability during AD processes. Industry 4.0 will be used as an example application. Creativity is generating valuable, new ideas. Innovation is making new ideas viable.
We will discuss how AD theory and methods can improve selection processes in evolution-inspired creativity for formulating functional requirements (FRs) and generating and selecting design parameters (DPs). FR formulation is a key to creating value in design solutions. No design solution can be better than its FRs. The FRs must capture the true, underlying essence of customer needs. In addition, FRs must define solution spaces appropriately, so that all the best DP candidates are included. Suh's axioms are used to select the single best DPs from the candidates. In AD, viability is established systematically during axiomatic decompositions and physical integration processes.
Methods for detecting poor design thinking will be presented and discussed, along with metrics and tests for evaluating FRs' facility for creativity and innovation and techniques for improving FRs.

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Procedia CIRP 53 (2016) 113 – 118

www.elsevier.com/locate/procedia

The 10th International Conference on Axiomatic Design, ICAD 2016

# Metrics for Developing Functional Requirements and Selecting Design Parameters in Axiomatic Design

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**Abstract**

This work studies the systematic use of metrics for developing design decompositions in axiomatic design (AD). The supposition is that a rigorous use of metrics will guide the formulation of superior functional requirements (FRs), and the selection of the best design parameters (DPs). Good FRs are essential for satisfying the customer needs (CNs). The metrics and equations relating FRs to their parents and to the corresponding DPs can be useful for complying with the axioms and for verbalizing FRs. Quantitative value chains, along with targeting and tolerancing chains, which start with the CNs, are proposed The use of adaptive designs, whereby a design solution can evolve to respond to changing circumstances, are also mentioned.


Peer-review under responsibility of the scientific committee of The 10th International Conference on Axiomatic Design

*Keywords:* parent-child equations; tolerancing; design equations; evolutionary design

## 1. Introduction

The selection of good functional requirements (FRs) is essential for design solutions that satisfy the customer needs (CNs). According to Suh, a design solution can be no better than its FRs [1]. This is true, limiting the result, no matter how well the axioms are applied after the FRs are developed.

The highest level FRs are based on CNs, which establish the value in the design problem. FRs translate the CNs into functional terms that can be used in engineering design. The CNs can be seen as the beginning of a value chain that extends through the FRs in the functional domain, to the DP solutions in the physical and process domains. The FRs continue this value chain, connecting to the design parameters (DPs) and the integrated solution. If everyone were to be using axiomatic design (AD) with equal effectiveness, then the competition to create the best design solutions would be to develop the best FRs. The best FRs are those that provide the best value for the customers. This must be captured in the formulation of the CNs and the development of the FRs.

The objective of this paper is to advance the techniques for teaching the development of FRs and the use of metrics for decompositions, starting with CNs. Parent and child and FR-DP equations are considered along with in the decomposition, se, tolerancing and adaptive, or evolutionary, designs.

This work is important because the fundamental supposition of axiomatic design is that proper application of the axioms leads to the best solution for a given design problem. The engineering design problem is defined by the FRs. Therefore a design solution can be no better than the FRs used to define the engineering design problem [1]. This view puts special burdens on developing FRs.

This work can also be important for learning and adopting AD. Failure of engineers to adopt AD often stems from difficulties with the formulation of good FRs. The hypothesis, proposed here, is that more rigorous attention to metrics throughout the decomposition will lead to better FRs and DPs and assist in assigning functional and physical tolerances and thereby improve the value of the resulting design solutions. This work advances the development of a systemic, quantitative determination of the quality of the FRs and DPs


Peer-review under responsibility of the scientific committee of The 10th International Conference on Axiomatic Design
doi:10.1016/j.procir.2016.08.045

with respect to satisfying the customer needs (CNs). This could be an element in a larger algorithm to automate some of the axiomatic design process.

### *1.1 State of the Art*

The process of developing FRs has been advanced by Thompson [2] for sorting out FRs from non-FRs and optimization and selection criteria. The concept that FRs must be collectively exhaustive and mutually exclusive (CEME) has been proposed previously [3]. And, Henley [4] has recently emphasized the usefulness of metrics in developing FRs.

There has been some work to develop techniques for improving the development of metrics for FRs. This work builds primarily on the need for CEME decompositions [3] and on metrics for FRs and how they should be used for verification of collectively exhaustive decompositions [4]. The requirements for a decomposition based on elementary combinatorics, set theory and partitioning, stating that the sum of the children must equal the parent have been developed and the importance of themes for verifying that a decomposition is CEME have been emphasized [3]. In addition the importance of semantics in the thought process while developing FRs and being able to argue convincingly that a decomposition is CEME has been presented [3]. Theses concepts also apply to the DPs. Henley [4] argues that the FRs should use metrics in order to establish that a decomposition is CEME. Henley also clarifies that the children are not required to simply sum to equal the parent, rather they can combine in any manner, in an equation, to equal the parent.

Thompson [2] dissects many things that have been used as FRs, sometimes by AD novices, and shows how in some situations there are several other FR-like entities that can be useful. These useful reclassifications include: non-FRs that describe the qualities or the character of what the design solution should be, and optimization criteria (OCs) and selection criteria (SCs) that are often indicated by the use of “maximize” and “minimize”. The OCs and SCs imply that there is a ranking that can be useful for selecting the best among candidate solutions. Ranking requires metrics and assigning values, of course. Thompson’s dissection of the FRs provides useful distinctions for intermediate and advanced AD users in addition to novices.

Thompson [5] presents a rigorous approach to considering the needs of customers and stakeholders. This is based on identifying several different stakeholders and stakeholder categories. This can be used to develop a check list that can be used to generate CNs that will be associated with FRs possibly at different levels in the decomposition. She also emphasizes the importance of being collectively exhaustive at this critical juncture in the development of the design solution, developing the initial FRs. Without recognizing the stakeholders, important CNs will be missed that would otherwise add value to the design solution. The missed CNs will probably lead to missed FRs and a less valuable design solution.

The mutually exclusivity i[3] is directly related to the independence axiom, which requires independence, i.e., mutual exclusivity, of the FRs. Different kinds of coupling have been examined [6]. FR-DP is the usual kind that is indicated by off-diagonal locations in the design matrix. FR-FR coupling can be more problematic because it might be less obvious. It results in a fully coupled portion of the design matrix corresponding the coupled FRs and could be mistaken for two instances of FR-DP coupling. However FR-FR coupling cannot be resolved by changing the DPs. Mutual exclusivity is required for compliance with axiom one and contributes to an axiomatic design process.

Metrics for the FRs have been emphasized in arriving at a design solution for play calling strategies in American Football [7]. Fixed and adaptive strategies are developed. The latter respond to changes in opponents’ strategies. In this instance it is shown that the having appropriate metrics improves the probability of success.

The intent of the design can be like the CNs and the design target has been called the equivalent in concept FRs [8]. This theory supposes that abductive reasoning, a logical inference using an observationally-based development method, to go from more abstract CNs to the more concrete concepts that are embodied in the FRs and then to the DPs. Liu and Lu [9] write about synthesis and analysis in axiomatic design and concept generation. They had good results for creating design solutions when compared with traditional brainstorming. Idea generation and validation are emphasized, although metrics and quantifying are not mentioned.

Matt [10] uses metrics in the development of the decompositions for the designs of manufacturing systems. Metrics specific to manufacturing, like takt time and units produced, are appropriately integrated into the decomposition.

Suh [11] introduces concept of the need for re-initialization in complex system design. This can be periodically or in response to a need that must be detected by monitoring. Matt [12] develops the theory and practice of re-initialization writing. A design solution can include the capacity to monitor and control complexities. These complexities reduce the probability of success, which address the fulfilment of axiom two. The design solution is adaptive in that it detects if a system range in manufacturing is deviating sufficiently from a prescribed range and can trigger a re-initialization. This is a kind of adaptive design solution.

### *1.2 Approach*

The supposition here is that the selection of metrics improves the transition from CNs to DPs and to FRs. The use of metrics and mathematical relations, especially during the development of the decomposition, is considered in the context of ease and confidence of the quality assessment. This use of metrics is similar to Matt’s work [7e], although here it is examined systematically as part of the decomposition process. The assessment of the quality of the solution is related to the success of the solution in providing value, and to the verifiability of the value during the design

process. The quality of a design process is also related to the capacity for teaching students to use AD to solve design problems effectively.

## 2. Methods

The methods used here are philosophical and experiential. They are rooted in practice with, and teaching of, AD. The techniques presented here for developing FRs and employing metrics have evolved during over 25 years of experience as a practitioner and teacher of AD. Some of the experience includes consulting with industry on design problems. Much of it comes from advising capstone engineering design projects and teaching a project-oriented graduate course on axiomatic design of manufacturing processes at Worcester Polytechnic Institute. The students in the course have been a mixed group of regular, full time students and part time students who, working full-time as engineers, bring industrial experience into the class. An objective in teaching full-time engineers AD is to provide them with something they can use immediately for their jobs. This has worked well. Most of the practicing engineers report that they have used AD at their jobs. This teaching experience provides opportunities to see a wide variety of interpretations, including misinterpretations, of proposed techniques and a range of applications and degrees of success. This is the feedback necessary for evolving the teaching methods.

### *2.1 Perspectives*

The use of metrics has been driven by the need to verify the quality of the design solutions. Twenty-five years ago a qualitative development of decomposition was taught at WPI. This was complimented with a quantitative definition of the design matrix. Partial derivatives were used to illustrate the coupling terms. The column vectors were reviewed and exercises were assigned to find the reangularity and semangularity [1]. There were also quantitative problems on axiom two, similar to those suggested by Suh (1990). However, the zigzagging development of the design decompositions was almost always qualitative. The metrics for FRs and DPs, if they were added at all, were generally added after the decomposition was finished.

In the early years the decompositions tended to be small, usually not exceeding about twelve FR-DP pairs. The introduction of Acclaro (Axiomatic Design Solutions, Inc. www.axiomaticdesign.com) allowed for much larger decompositions. A design for one consulting project exceeded two thousand FR-DP pairs. Acclaro software facilitates zigzagging decomposition and construction of qualitative design matrices.

Verification of the quality of the decomposition of a design solution, for both FRs and DPs, is based on the CEME requirement. In the absence of metrics, this argument, can strive for a logical basis by using a theme to expand the parent into children. When it is non-quantitative it is difficult to verify. Many students simply declare that their decomposition is CEME. This is non-verifiable and clearly unsatisfactory.

The evaluation of the decomposition is not so much for academic grading. as it is for the designer to self-critique and self-correct and thereby improve the design. The evaluation should increase the likelihood that the design solution will successfully satisfy the CNs.

### *2.2 Generalities*

The design hierarchy is developed as a decomposition of the design solution, top-down, in a zigzag manner. The objective is to satisfy the CNs. The upper levels act as constraints on the lower levels [1]. The lower levels need to be consistent with the upper level of the decomposition. The use of parent-child equations, discussed below, can assure this consistency.

The decomposition needs to be CEME to be valid, that is, an actual decomposition that is complete and potentially useful for a design solution that complies with the axioms.

The decomposition process starts with the customer needs (CNs), which should establish the value. The value must be maintained through the domains and down the hierarchy. Some parts of the CNs should be constraints, non-FRs, OCs, or SCs [2].

The designer must maintain a distinction between the functional and physical domains. The FRs should be stated in a solution neutral environment, so as to maximize the solution space for selecting DPs. If the FR contains physical information, the design solution space becomes limited and the best design solution might not be considered. Including physical information in the FR is contrary to the AD process.

Axiom one demands mutually exclusivity of the FRs. Axiom two clearly applies to the selection of the DPs, although it also could apply to how well the FRs can provide value to the customers. In a decomposition the children must be collectively exhaustive with respect to parents. FR metrics should be used [4] to verify this. Parent-child (in one domain) and design (between two domains) equations should be developed during the decomposition.

FR0 should start with the active verb for the thing you are designing. Avoid starting with “design” unless you are designing a design process. Starting FR0 with the word “design” is a frequent mistake with inexperienced users of AD. An FR0 like “design a bicycle” is only appropriate if the CN is something like “produce designs for bicycles”. There is another potential problem with an FR0 that mentions a bicycle. The word “bicycle” already suggests a physical design solution. Almost everyone thinks of two wheels and a frame when they see the word “bicycle”. If the goal is to discover if there might be something other than a bicycle for self-powered personal transportation or pleasant exercise, try “transport people under their own power” or “provide exercise with changing scenery”. In other words, the designer should start with the CN and formulate an FR that is completely void of physical information about the solution.

### *2.3 Design solutions with evolving strategies*

Two kinds of solutions are considered here: fixed and adaptive, or evolutionary. Fixed solutions are adjustable and controllable to respond to a more limited and relatively static set of circumstances and only require adjustments to the value of the current DP. There are also evolutionary, dynamic or adaptive, design solutions that are intended to evolve new design solutions. These adaptive design solutions adjust to circumstances that are changing in a larger sense and require new DPs [7].

Examples of fixed, quasi-static design solutions might be some kinds of "continuous improvement systems", such as are used in lean manufacturing [7f]. These kinds of design do not require new DPs. The DP is a system that continuously strives for improvement and can satisfy CNs over long periods.

Evolutionary design solutions are intended to adapt to larger changes in circumstances that require new DPs. Evolutionary designs might be used to address changes in a competitor's strategy or product that could require some redesigning of the current strategy or product as initially designed. These kinds of adaptive solutions, for addressing larger changes in the circumstances or environment, need to include some kind monitoring to know when these changes are large enough to trigger a response.

An example of such adaptive designs that evolve to respond to changing circumstances is given for play calling in football where the other team changes their play calling strategy because the opposing team has changed theirs [6]. If both teams are using an adaptive strategy, then the quest would be to adapt, or evolve, faster than the competitor. This is a concept that is understood in many competitive endeavors.

In AD the ability to evolve by responding to changes in the environment or in an opponent's behaviour can be addressed by placing FRs at appropriate places in the hierarchy and branches. Typically these kinds of FRs would have the children to address monitoring, or measuring key indicators, analysing these measurements, and responding appropriately. Adaptation, or the ability to evolve, can be a top level FR or it can be distributed appropriately in the branches.

FRs that begin with terms like maximize or increase might be evolutionary if they have an appropriate solution decomposition. They also can be OCs or SCs [2]. If they are to be evolutionary then the design solution needs to include monitoring, analysis and response functions.

## 3. Results and Discussion

### *3.1. Leading with metrics*

Deciding on appropriate metrics for the FRs before choosing the DP, even before verbalization, can be effective in developing superior FRs. The supposition is that metrics for the FR, or functional metrics (FMs), facilitates the verbal definition of the FRs and the application of the axioms. The metrics for the FR should indicate how well the CN is being satisfied. This would be different than how well the customer is responding or how sales are going. The FM should indicate what would be measured to see if this particular FR is fulfilling its intended function. It should be a measurement of the accomplishment of the function that the DP, the physical design solution will ultimately supply. The FM should be responsive to the question: what would you measure if you were tasked as an engineer to assure that that function was fulfilled.

The metrics can also be useful for discussing with customers and other stakeholders early in the design process to be sure that the design efforts are providing the intended value and avoiding unnecessary expenses.

Sometimes there is a tendency to propose that the metric is binary, that its mere existence is all that needs to be verified. The designer should be cautious in accepting binary verifications instead of measures of quality. To develop a more valuable, quantitative metric the designer needs to consider what might constitute more or less valuable versions of the solution.

### *3.2 Equations for the decomposition: design and parent-child*

There are two kinds of equations that should be part of the decomposition: parent-child equations that show how the children combine to equal the parent, and design equations that show how the DPs relate to FRs. The former is a kind of intra-domain equation and the latter is an inter-domain equation.

Naturally, the writing of equations is facilitated by the selection of appropriate symbols for representing the FRs and DPs. These symbols should be chosen to be specifically related to the metric, as opposed to the more generic FR1, FR2, etc.

Writing specific design equations can be difficult at the higher levels in particular. This is because at these levels the FRs are more abstract and the upper level DPs often represent systems that are composites of many elements. The effort to write the upper level equations can assist in the decomposition by suggesting the detailed content of the upper level FRs and DPs. When it is not obvious what the details of the design equations should be, they can be left as unknown functions. Nonetheless these should attempt to specify all the symbols for all the DPs that will influence each FR.

The parent-child equations need to show how the children combine to equal the parent. Previously this combination has been referred to as summing [3]. The use of all the children in any kind of mathematical expression should be acceptable in the parent-child equations. In some situations plots or tables can be acceptable, although in no case can a parent be decomposed into only one child. There must be at least two children for each parent.

The language used to describe the children should be similar to that used to describe the parent. The child FRs and DPs should inherit critical attributes from the parent, this includes the phraseology.

### 3.3 Targets and Tolerancing

Knowing what should be measured, i.e., selecting the right metrics, is required for setting target values and tolerances. It is important to keep these distinctions clear. When asked to specify metrics students occasionally and wrongly provide the target values. Initial design decomposition can be accomplished with metrics and without determining the values for the metrics.

Often the target values and tolerances for the metrics should be determined during the decomposition phase. Sometimes when the required dimensions for a component are calculated it is discovered that it will not fit into the space allotted Sometimes it is discovered that a feature violates some other constraint. This kind of problem would initiate a change in the design solution that impacts the decomposition. Excessive calculation and design changes during detailed drafting (CAD) can be indications that the decomposition phase was not sufficiently quantitative.

Targets and tolerances can be understood for the CNs. These should be transferable to the FR and should be part of the development of the FR and its metric. If the design equation relating the FR and DP has been developed properly then the calculation of target values and tolerances in the physical domain should be straightforward. There should be a clear value chain for the physical tolerances on the detailed engineering drawings that connects through the functional domain to the customer.

### 3.4 Considerations for manufacturing process design

Manufacturing process design can be considered in a chain from FRs to DPs to PVs [1, 13], although here it will be considered separately as FRs for the manufacturing process to DPs [14]. The role of manufacturing is to create the required or desired value and control costs [13, 15]. Accomplishing these directives clearly benefit from appropriate metrics.

In fabricating mechanical parts there are universal concerns: achieving the desired form, or shape, i.e., large scale geometry, and the right surface texture, or roughness. In this view of manufacturing FRs and DPs it would be appropriate to design a manufacturing process where achieving form and surface roughness are ends in themselves. The larger picture would address why that roughness is needed, however this can be outside the scope of manufacturing process design.

This suggests two FRs: one for achieving the prescribed form, and one for achieving the prescribed surface roughness. The metrics for the form and texture FRs would be the probability of achieving the dimensional and the roughness tolerances. The appropriate metric could be repeatability. The measure for repeatability could be the standard deviation at some level of the hierarchy. From this the probability of success and information content could be calculated (Suh 1990). The FRs for achieving tolerances might be high level thereby applying to everything, in a kind of distributive manner, or they might be distributed throughout the branches.

In an adaptive design an adaptive FR could be called “control the variability” perhaps applying to a specific feature. The DP could be a “variability control system”. The DP might be intentionally vague at this point in the process of developing the decomposition. The design equation relating this FR and DP could be similarly vague. The designer would select variable names and write equations, like V = f(S), where V is the standard deviation and S is some physical measure of the control system or control device. The function might determined analytically and tested experimentally. An increase in variability could indicate wear or change in temperature and would trigger maintenance or improvement in temperature control.

## 4. Concluding remarks

A number of concepts relating to the use of metrics in the process of developing a design solution axiomatically have been discussed. Some of these concepts might seem obvious, although all have proved challenging for some graduate students over time. The experience has been that the emphasis on metrics improves the design process and elevates the comprehension. All of these concepts would benefit from further development and the publication of case studies using these concepts, such as done by Matt [12]. Specific steps should be laid out for the inclusion of metrics and integrated into a synthesis and analysis design development system, such as shown in Liu and Lu [9]. The systematic application of adaptive design systems that go beyond re-initialization [11. 12] to re-design, as used in play calling for football [7] for defining new DPs and possibly new metrics and FRs.

## Acknowledgements

The authors gratefully acknowledge the support of the Manufacturing Engineering Program at WPI for graduate teaching assistantships for co-author Henley, and of Andy Corsini of Supfina Machine Company in North Kingston, RI for supporting the study of the application of AD in managing a corporation. Thanks to Matt Pallaver for generously providing the use of Acclaro to universities for teaching AD, and to Professor Nam Suh for his interest and encouragement in our work.

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Procedia CIRP 53 (2016) 206 – 212

www.elsevier.com/locate/procedia

The 10th International Conference on Axiomatic Design, ICAD 2016

# Axiomatic Design Applied to Play Calling in American Football

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**Abstract**

The objective of this paper is to learn if the use of functional metrics and the use of parent-child equations can guide design decompositions for winning games. This study is performed in the context of designing play calling strategies in American football. The top level functional metric for FR0, outscore your opponent, is "point differential", which is controlled through the child metrics that comprise it. Using an on-line game simulator based on statistics from the 2015 season, in over 96 simulated games, two design solutions are tested statistically against last year's results in the National Football League (NFL). The results show that the solutions based on the application of functional metrics increase the number of wins compared with the actual results from 2015. This suggests that whatever system the NFL coaches were using in 2015 was not the best for winning.


Peer-review under responsibility of the scientific committee of The 10th International Conference on Axiomatic Design

*Keywords:* American football; functional metrics; design decomposition; return on investment; axiomatic design

## 1. Introduction

American football provides an interesting opportunity to test the use of axiomatic design to create a game strategy. It is a highly structured game composed of a series of short precisely predefined and well-rehearsed "plays" where each player has a specific task. In between these plays the players and coaches can consult on the next play to call. The players line up in special formations before each play. Play calling strategies are designed here and tested in game simulations.

This work tests the utility of functional metrics (FMs) and the use of parent-child equations for guiding the decomposition of a design for winning games. The hypothesis is that controlling appropriate FMs can increase the likelihood that a team can outscore their opponent. The scope of this paper is designing play calling in American football games. In a more general sense it is applicable to other games and situations that rely on scores to determine success. For more on scoring and ball control in American Football see Appendix 1.

Metrics here are used to determine the degree of success of a system or process. An FM indicates how well a functional requirement (FR) satisfies a customer need (CN). Parent FMs relate to their children through parent-child equations that are expressed between all levels of the decomposition hierarchies. Upper-level FMs can be considered dependent variables, and the children FMs are the independent variables that combine to equal parent FMs [1].

FMs can be important for several reasons. Having FMs at every level can facilitate a decomposition that satisfies axiom one by being collectively exhaustive mutually exclusive (CEME) [2]. CEME means that the children are collectively exhaustive with respect to the parent and mutually exclusive with respect to each other. CEME applies to decompositions in all domains. Having an FM and a parent-child equation for each FR and design parameter (DP) provides a quantitative path for the determining children FR-DP pairs.

Without being able to quantify a system's current state, it cannot be objectively determined whether the system is improving or the amount of improvement [1].

When the system is underperforming, it can be difficult to trace the cause without FMs [3]. An evolving design solution must be able to identify and adjust underperforming elements within the solution. FMs at every level can facilitate


Peer-review under responsibility of the scientific committee of The 10th International Conference on Axiomatic Design
doi:10.1016/j.procir.2016.08.010

identification and adjustment of underperforming elements.

NFL (National Football League) teams currently invest resources apparently to prioritize metrics that are not the best indicators for winning games. Certain positions on the field are considered more important for achieving certain metrics and can be given a larger percentage of the salary allotment, which is capped by the league.

There can be times when internal or external factors cause certain FMs within the design solution to no longer be as beneficial. This might be a result of reaching maximum capability or because the opponent has made an adjustment that your design solution is not well adapted to handle. A regular review and possible alteration of the design solution can prevent obsoletion of the design solution.

The techniques for the development of strategies and tactics for play calling in American football might also be applied to developing strategies and tactics for other sports and for business and government or military applications as well.

### *1.1. State of the Art*

Due to the competitive manufacturing environment of the 1980s, organizations began investing effort into developing performance measurement systems that measured the effectiveness of the organization's processes [4]. The performance-measurement record sheet [5] provides a list of criteria that must be present for a metric before it can be considered actionable.

Lewis [6] writes about the failure within US Major League Baseball to identify the right metrics. The 2002 Oakland Athletics were able to win the most games of any team in the league during the regular season, despite paying the third lowest salary to their roster by prioritizing metrics that correlate more strongly with wins.

Decision-making in football has been analysed based on the expected point value (EPV) [7, 8]. The EPV is based largely on the position on the field and is in fact the amount of points a team should be expected to score on average by having a first down at the current field position. This was developed by Carter et al. [7] by analysing data from the 1969 NFL regular season. With an EPV of 0 at one's own 20 yard line, EPV increases roughly 1 point per 18 yards and can also be valued negatively, with a value of -1.25 at one's own 5 yard line [9]. A common theme in the literature is that decision-makers for most teams during a game tend to be risk-averse in 4$^{th}$ down situations, to the point of reducing their chance to win. This is due to making play calling decisions that reduce to total EPV over the course of the game [7, 8].

Suh [10] gives many examples of decompositions with metrics for the FRs and DPs. He proposed that ROI (return on investment) can be decomposed to three main FRs: (1) increase sales revenue, (2) minimize cost and (3) minimize investment. His design decomposes the FM equation for FR 0, ROI = (Sales-Cost/Investment). The next level of FRs and DPs are used to control each variable in the equation independently. Manufacturing System Design Decomposition (MSDD) was similarly designed using the same 3 three top level FRs as Suh [10] to satisfy the goal of maximizing return on investment [11]. Collective System Design is a method based on axiomatic design (AD) theory [12]. This system provides a behaviour and process for collective agreement during a company's conversion to lean, to achieve long term sustainability. This includes assigning metrics to FRs and DPs.

An initial design solution can adapt through a regular review and adjustment of the FMs to ensure that the design solution continues to be valuable. This kind of adapting design solution can save an organization the expense of having to develop a new performance measurement system [13]. The performance paradox model [14] explains the inevitable need for evolution as a requirement in every performance measurement system. A new set of metrics will need to be defined that measure the same value to the customer if the success rate of current solution becomes stagnant or moves in an undesired direction.

According to Cochran et al. [12] there are three options when the FMs are not acceptable:

(1) Improve the standard work without changing the physical solution (PS)
(2) Determine a new PS
(3) Change the respective FR.

### *1.2. Approach used here compared to the state-of-the-art*

Similar to Suh [10] and Cochran et al. [11], AD is used here as the framework for the two design solutions, initial and adapting. However, unlike those authors, but similar to Henley [1], they will feature FMs and parent-child equations at every level. Similar to Brown [2], this design is an attempt at a CEME solution. Unlike his work, FMs and parent-child equations are used as a quantitative method for determining CEME. Similar to Bruns [4], Suh [10] and Cochran et al. [11], ROI is a top level FM for success. However, in this situation the return will be measured in points. Similar to Neely [5], the performance record sheet is used to determine actionable lower level FMs that control the top level FM. Similar to Lewis [6], the play calling strategies in this work will prioritize controlling lower level performance related FMs.

The play calling strategies here are intended to maximize the EPV in each game and in each series of plays and minimize the opponent's EPV. Similar to Carter et al. [7] and Urschel et al. [8] decisions on 4$^{th}$ down will be made to increase the EPV as opposed to a more risk adverse strategy that tends to favor punting and field goal attempts.

Also, similar to Cochran et al. [12] and Kennerley and Neely [13], the design solution must be able to be altered when it is underperforming. Similar to Cochran et al. [12], the method for addressing an underperforming FM is to first improve the standard work. One example situation might be controlling the metric for the time it takes to rush the quarterback. Improving the standard work could be changing out a player for one who is faster and therefore rushes the quarterback faster. If improving the standard work is not sufficient, the next option is to alter the DP. An example of this could be changing to a play that increases the number of players rushing the quarterback.

Unlike Cochran et al. [12] who suggests the possibility of defining new FRs as a possibility for improving performance, new FRs are not considered over the course of testing these design solutions. Unlike Meyer and Gupta [14], who suggest the possibility of defining new metrics as a possibility for improving performance, new metrics are not considered over the course of testing these design solutions.

## 2. Methods

### *2.1. Formulating two solutions*

Fig. 1 shows the top two levels for the first design solution and FM equations for the third level. Both solutions are designed using axiomatic design and have the same FR0, FM0 and parent-child equations. The difference is that for the second design solution, DP0 is "Adaptive play calling strategy."

The FR is defined to control the related FM, in this case FR0 is outscore your opponent and FM0 is point differential (PD).

The DPs define the scope of the design of the FRs and DPs at the lower levels, i.e., constrains them [15].

Each FM's parent-child equation determines the next level of the decomposition [1]. Each lower level FM is a variable in the corresponding parent-child equation. FM 0 and its related parent-child equation are shown in Fig. 1.

PD depends on PSF and PSA. To control PD the user must control the two variables PSF and PSA. Thus there must be two FM-FR-DP sets at the next level, one to control PSF and the other to control PSA. As the solution for controlling the FM is not obvious, the FMs must then have their own children and parent-child equations to determine which lower FMs they are dependent on. This cycle is repeated until the solution for controlling the lowest level FMs is obvious. Sometimes the variables in the related equations are known but the exact formula for their combination is unknown. FM 1.2 is an example of that situation. Controlling the number of offensive possessions is a function of controlling the number of interceptions and fumbles in favor of the user's team. However, the exact form of the equation might not be known. The full decomposition, with the FMs, extends for five levels.

In the adapting design solution each FM has a time derivative to indicate when the design solution requires evolution.

If the derivative over time of any of the FMs stagnates or trends in an undesirable direction, changes to improve the standard work are made. If this does not solve the problem then a new DP is chosen.

### *2.2. Testing the solutions*

An online, comprehensive, statistic-based game simulator called *Action! PC Football* [16] was used to test the play calling strategies. This simulator mimics the performance of each team and their opponents from the selected season. The users call the plays and substitutes players. The statistics from the selected year are used to calculate results of each play called.

Three NFL teams were selected to represent the top, middle and bottom of the results from the actual season. The 2015 season was simulated for each of the selected teams, once with the fixed and once with the adaptive play calling strategy solution.

In both fixed and adaptive solutions the play calling choices are made to maximize the EPV of each series. EPV is FM 1.1, and is controlled by controlling the number of first downs and starting position of each series. Each play is chosen to consistently increase the EPV of that current series. Each position on the field has a specific EPV. On 1st, 2nd and 3rd down the play with the highest probability of forward progress is chosen in order to get the next first down, thus increasing the EPV of the series. During each 4th down, an equation is used to determine the EPV of three scenarios (1) going for the first down, or the touchdown if the goal line is closer than the distance required for a first down (2) punting (3) kicking a field goal. Whichever has the highest EPV is the choice made [7].

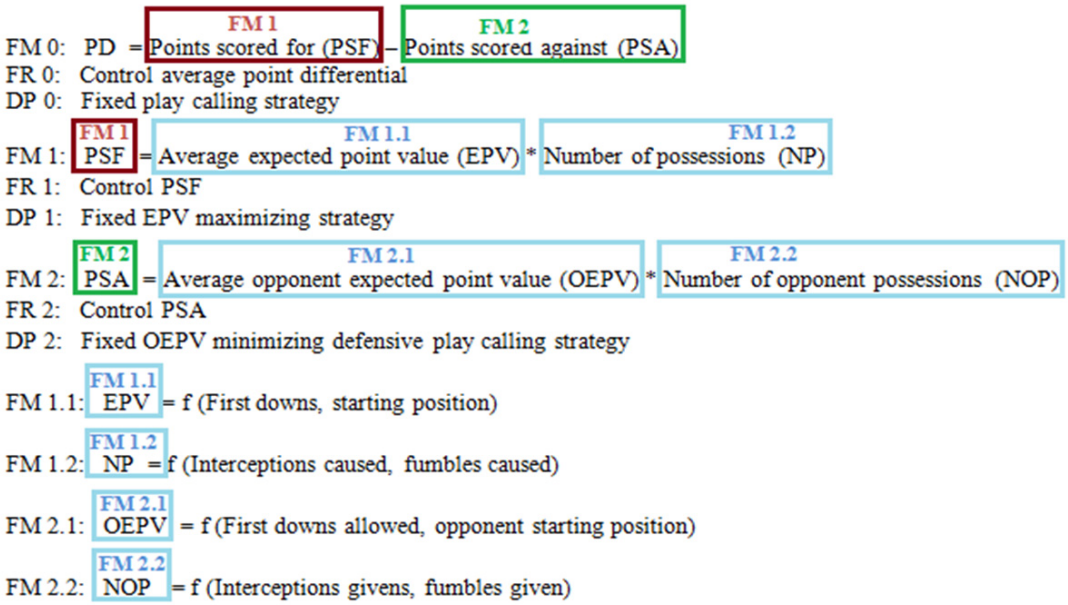


Fig. 1: Top two levels of the 5 level fixed play calling strategy design solution and FM equations for the third level

An example to illustrate making a decision using EPV would be 4th down at 5 yards to go on the opponent's 5 yard line. The user has two choices, kick a 3 point score or go for the touchdown. Based on Carter et al.'s [7] data, the probability of a making a 3 point kick can range depending on the quality of kicker and the angle, but is about 75% on average. The probably of making a touchdown for 7 points is about 25% on average. The equation for EPV considers both the chance of the getting points combined with the EPV for succeeding minus the EPV from the resulting opponent's field position if the attempt to score fails. If the field goal is missed the opponent will begin their series on their 15 yard line (-0.64 EPV). If the touchdown fails, disbarring a turnover or loss of yards, the opponent will begin their possession somewhere between their 1 and 5 yard line (-1.3 EPV).

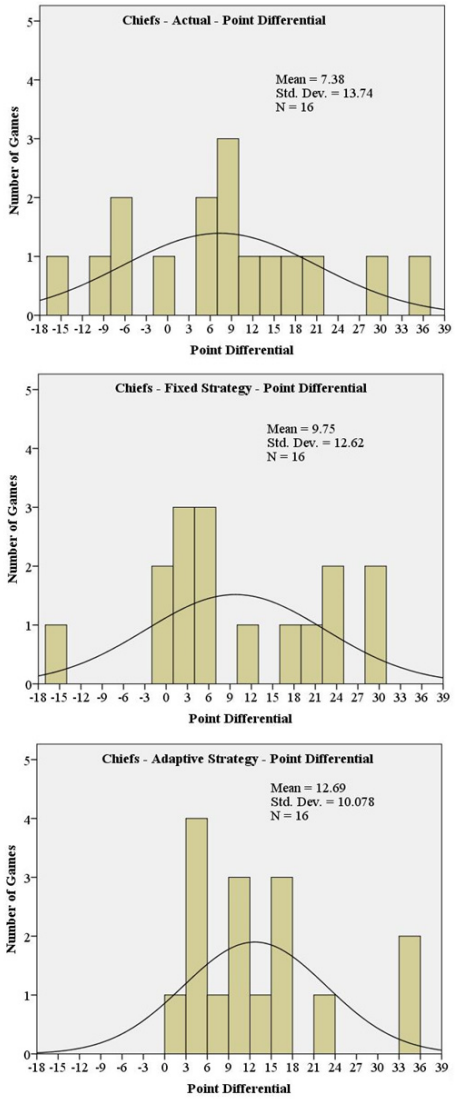


Fig. 2: Chiefs' means and standard deviations histograms

The equation for the field goal option (FGO) would be (1):

$$FGO\ EPV = \left(\left(0.75*3\right) - \left(-0.64\right)\right) = 2.89 \quad (1)$$

The equation for the touchdown option (TDO) would be (2):

$$TDO\ EPV = \left(\left(0.25*7\right) - \left(-1.3\right)\right) = 3.05 \quad (2)$$

So in this situation, using the design solutions in this work, the user would make the choice to go for the touchdown due to higher EPV.

Two changes were made to the settings for the simulations. All penalties were removed from simulations for the adaptive play calling strategy simulations. This is due to what seemed to be an uncharacteristically large number of penalties for fighting and other fouls for unsportsmanlike conduct. These are not related to the play calling, yet they can alter the result of a series, because they often grant an unearned first down. Also, the simulator features a limiter that forces injuries on a player if their yards gained on the simulated season will significantly exceed their actual totals. That limiter was switched off. This change does not prevent players from becoming injured as a part of the result of a play.

### *2.3. Comparing the two solutions: fixed and adaptive*

The two design solutions have a few play calling differences.

With the initial, or fixed, design solution, the user chooses the offensive play that has the highest probability of success and a positive gain, factoring in what is needed to likely achieve the next first down. These gains are usually small, ranging between one and ten yards regularly, however they can consistently be relied on for a gain. The *Action! PC Football* simulator [16] displays the probability of a positive gain with each possible play choice.

There are some situations where the user calls plays with a lower probability of successful completion on 2nd or 3rd down This is due to a negative result on a previous down. To get 10 yards over 3 plays, the user needs at least 3-4 yards on average each play. Sometimes a play can result in no gain or a loss of yards, requiring the user to gain over 10 yards in 1 or 2 plays to achieve a first down. The user must then consider choosing a play that has a lower probability of a successful completion but can result in a longer gain. This is because the plays with the highest probability of successful completion are unlikely to result in the larger gain needed for a first down.

The defensive play is always the same, based on the FM of minimizing the time the opposing quarterback has to deliver the ball. This depends on the number of pass rushers and when receivers get free from defenders. Therefore a minimum of 5 players rush at the quarterback every play. In conjunction, the pass defenders play tight man on man defense to limit the quarterback's options.

At the start of the game, the adaptive design solution uses the offensive play calling strategy of the fixed design solution.

The derivative over time for each FM is monitored and changes are made if the values of the current FMs trend in an undesired direction. Similar to Cochran et al. [12] attempts to improve the standard work are made, and, if unsuccessful, a different DP can be chosen. Offensively, this DP might be the type of play being called. Similarly on defense, the number of players rushing the quarterback, the number of players in pass defense and the scheme can change as they are the DP for controlling their related FM.

Sixteen games, a full season, are played on the *Action! PC Football* simulator [16] using these strategies. The value of each FM is recorded at the end of every game and totaled for the season. The means and standard deviations for the top two levels of FMs are calculated for both design solutions and compared to those from the actual season.

## 3. Results

For each simulation the mean and standard deviation for points scored, opponent points and PD have been collected. The results of each design solution are compared to each other and to the actual season. Fig. 2 is an example of the compared means and standard deviations for PD. In this case, the figure shows comparisons in PD while using the Kansas City Chiefs. This specific data set was illustrated as it best represents the expected improvement when applying the design solutions. There is noticeable improvement in PD with the design solutions compared to 2015 play calling strategies, PDs of 9.75 and 12.69 for fixed and adaptive compared to 7.38 for actual. Similar results for lower level FMs can be found in Henley [17].

The means and standard deviations for PDs for the all three teams for the actual season and the fixed and adaptive design solution strategies are compared in Tables 1 and 2.

Table 1 shows the means for the FMs of the design solution's top two levels. The mean for points scored and PD for each team was higher with the design solutions' play calling than during the actual 2015 season [17].

The adaptive play calling design solution does not always do better than the fixed play calling strategy. The mean PD was lower for the Seahawks using the adaptive strategy.

The opponents points scored did not always go down with the design solutions compared to the actual season.

Table 1: Means for the regular season's 16 games

| *Means:* | **Actual** | **Fixed** | **Adaptive** |
|---|---|---|---|
| **Seahawks** | | | |
| Points scored | 26.44 | 36.13 | 31.00 |
| Opponent points | -17.31 | -15.50 | -21.25 |
| **PD** | **9.13** | **20.63** | **9.75** |
| **Chiefs** | | | |
| Points scored | 25.31 | 31.63 | 33.00 |
| Opponent points | -17.94 | -21.88 | -20.31 |
| **PD** | **7.38** | **9.75** | **12.69** |
| **Browns** | | | |
| Points scored | 17.38 | 25.19 | 26.94 |
| Opponent points | -27.00 | -29.56 | -23.63 |
| **PD** | **-9.63** | **-4.38** | **3.31** |

The standard deviations for points scored, opponent points and PD were smaller with the design solutions' play calling than during the actual 2015 season (Table 2). There is an increase in the standard deviations for opponent points scored in the fixed solution compared to the actual season.

Table 2: Standard deviations for the regular season's 16 games

| *Standard deviations:* | **Actual** | **Fixed** | **Adaptive** |
|---|---|---|---|
| **Seahawks** | | | |
| Points scored | 8.39 | 9.12 | 7.63 |
| Opponent points | 11.75 | 8.30 | 7.92 |
| **PD** | ***14.12*** | ***11.59*** | ***9.44*** |
| **Chiefs** | | | |
| Points scored | 8.95 | 8.85 | 6.79 |
| Opponent points | 9.77 | 10.07 | 5.37 |
| **PD** | ***13.30*** | ***12.22*** | ***9.76*** |
| **Browns** | | | |
| Points scored | 8.71 | 7.67 | 8.66 |
| Opponent points | 7.17 | 10.55 | 6.25 |
| **PD** | ***12.7*** | ***10.89*** | ***10.1*** |

The standard deviation of the adaptive strategy could be somewhat misleading (Table 2). Excluding what could be two outliers with PDs was in the 33-36 range, positive results that exceed expectation, the standard deviation was 6.

Table 3 shows the actual, fixed and adaptive strategies win-loss records of the teams. The record for each team was better with the design solutions than the actual 2015 results. The adaptive play calling design solutions results in the best win-loss records overall.

The adaptive play calling design solution in particular offers the greatest advantage when comparing the three top level FMs included in this work. The play calling strategies designed by AD achieve better records than the actual 2015 season's play calling strategies.

Table 3: Win-loss records for the regular season's 16 games

| *Win-loss records:* | **Actual** | **Fixed** | **Adaptive** |
|---|---|---|---|
| **Seahawks** | 10-6 | 16-0 | 15-1 |
| **Chiefs** | 11-5 | 13-3 | 16-0 |
| **Browns** | 3-13 | 6-10 | 11-5 |

## 4. Discussion

This design process could be applicable in other sports and situations requiring winning strategies. Also, AD is more than the decomposition and metrics, which have been emphasized here. It is about compliance with the independence and information axioms. Independence is maintained (axiom one) during the decomposition in part by being CEME and the FMs help to accomplish that. In addition, minimizing information (axiom two) can be re-stated as maximizing the probability of success in fulfilling the FRs. The attention to the probability of success used here in selecting the plays, e.g., the EPV, works to comply with axiom one.

The results indicate that the design solutions in this work are superior to actual play calling in 2015. However, these results cannot be considered the same as actual games. Using a simulator, the user is able to bypass possible obstacles like

player and team staff buy-in to what might be considered a radical play calling approach. The simulator also allows the use of players far beyond the point that the coaching staff would have removed them for fear of injury.

### *4.1. Mean PDs*

The mean for points scored for each team was higher in the design solution's data than during 2015. The PD was also higher in the design solutions than during 2015**.** This might indicate that the design solutions feature a more effective offensive play calling strategy than was used in 2015. The histograms for PD in Fig. 2 for the adaptive strategy show particular improvement to 12.69 in part because there are no instances of negative PD due to an undefeated season.

There could are three reasons why the opponent's average points scored increased overall. The first is a choice to prioritize certain FMs that give the opponent higher yards gained per play but favors turnovers, compared to the actual 2015 season. The second is because as the users increase their number of scoring possessions, the opponent will have more possessions. The opponent's average points scored might increase but the users' increase more. The third reason is that at the end of the game when one team is almost guaranteed victory, different choices are often made. The defensive play scheme moves to prevent long gains and quick scores and allows the opponent to make short gains more easily. This runs out the playing time, limiting the chances for the opponent to catch the score the users.

The win-loss records are one possible result of a high positive point differential. Even though there are some undefeated seasons, the same point differential over the entire season could occur with a worse win-loss record. A higher positive point differential increases the chances of but does not guarantee wins.

### *4.2. Variation of the PDs*

The standard deviations for points scored, opponent points and PD were smaller for the design solutions than during the 2015 season. This shows that not only are the users outperforming the opponent but the users have greater control over how much they outscore the opponent by.

One surprising result is how low the standard deviation is for the opponent's points scored. This shows that the design solutions outperform the actual 2015 play calling strategies. This is possibly more important than an improvement in the means for each stat. Improved certainty (reduced standard deviation) is an important result when designing solutions with AD because it reduces the information content (axiom two). A good design solution offers the user better control, i.e., less uncertainty.

The results for the simulated season for the Seahawks using the adaptive play calling strategy, with the one loss, might be an outlier. The two starting running backs and four of the five starting offensive linemen were injured most of the season, as was the highest scoring receiver from the fixed strategy simulation. This is not something that commonly occurs in a single season. This reduced the probability of positive gains on every play and inhibited the ability of the team to score points consistently. As a result, the opponent had the ball more often than they normally would have and therefore scored more points.

### *4.3. Metrics*

Every simulated season had the user's team in last place in the league in every passing statistic except the completion percentage, in which each team was in the top five. Yet even so, each simulated team surpassed the PD of the team during the actual 2015 season. Many consider these passing statistics important.

This might suggest the current allocation of salary, within the league-imposed cap, by position can be improved. The increased use of running backs led to many injuries on the offensive line and to the running backs during the simulations. Teams might be better prepared to outscore their opponents with more money spent on the offensive line and running backs and less on the quarterback.

## 5. Conclusions

Several things can be concluded from this work: First, axiomatic design (AD) can be used advantageously to design game-winning strategies in American football. Second, AD with functional metrics (FMs) and their related parent-child equations facilitate top-down decompositions for the design of play calling strategies, which provide for scoring points and preventing the opponent from scoring points and clearly have applications in other competitive situations in games and business. Third, the key metrics resulting from the application of AD with FMs for evaluating performance details are different than many of the metrics commonly thought to be important in American football, e.g., passing yards. Fourth, play calling strategies created with AD using FMs, for both fixed and adaptive design solutions, appear to be better for winning games than the actual play calling used in the NFL.

Future work should test extending this approach, using functional metrics rigorously to other games and competitive situations. FMs and adaptive designs should be developed so that they can be applied systematically to a broad range of situations.

## Acknowledgements

The authors gratefully acknowledge the support of Prof. Richard Sisson and the Manufacturing Engineering Program at WPI for graduate teaching assistantships for co-author Henley, and of Andy Corsini of Supfina Machine Company in North Kingston, RI for supporting the study of the application of AD in managing a corporation. Thanks to WPI's football coach Neil Hitchen for providing us with the opportunity to see our ideas in motion in college games. Thanks to Matt Pallaver for generously providing the use of Acclaro to assist in this work. Special thanks to Liam Koenen and Camden Lariviere for selecting us to advise their senior thesis (Koenen and Lariviere 2016) and assisting in the development of some of the methods used here. Thanks also to Professor David

Cochran of IPFW for his advice and Professor Nam Suh for his interest in this work.

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## Appendix A. Scoring and ball control in American football

Six points are scored when one team brings the ball across the opponent's goal line into the opponent's end zone, and then a seventh point can be scored by kicking a "point after".

The playing field between the end zones is one hundred yards long. At the beginning of each half and after each score the play starts with one team kicking off to the other. The other team can run it back until they are stopped and the ball is "downed", marking the position on the field for the start of the next play.

Offensive plays can involve combinations of running, when the ball is carried, or passing, when the ball is thrown. There are precisely defined roles and routes for each player which are play dependent. Each play continues until the ball carrier is tackled to the ground or forced out of bounds, which downs the ball.

If the offensive team has not progressed at least ten yards in four plays, or downs, then they must turn the ball over to the opponent. Therefore, on the fourth down the offensive team often decides to "punt", i.e., kick the ball down the field, thereby giving the opponent a less advantageous starting position for their series of plays. The other options are to "go for it" to see if they can manage the rest of the ten yards on the fourth play, or to try for a field goal, i.e., kicking the ball between goal posts, for three points.

If the offensive team has progressed at least ten yards in four downs, i.e. with four plays, or fewer, then they are awarded a "first down" and start again trying to get another ten yards in four downs or score.

The defensive team also has plays that often attempt to anticipate a pass or run type offensive play.

The offensive team can lose the ball as described above on downs or a punt or due to a "turnover", where a runner drops the ball in a "fumble" that is recovered by the defensive team, or where the defensive team intercepts a pass. Play then continues until the ball is downed or the defensive team scores a touchdown. The defensive can also score 2 points with a "safety" where they tackle the ball carrier in the offensive teams own end zone.

Before each play the players and coaches can consult to decide which play to run. To begin each play, the offensive and defensive players line up on either side of the ball, where it was previously downed. Once they see each other's line up they can call "audibles" to change their plays. The play starts when the "center", an offensive player who lines up on the ball, "hikes" the ball to the "quarterback".

The moment the center moves the ball the players can cross the line where the ball was placed separating the two teams. The quarterback then can hand the ball off to a running back for a running play, or pass the ball to a receiver for a passing play. The quarterback can have several receivers to pass to, depending on the defensive coverage. Defensive players can rush the quarterback, guard against a run or cover potential receivers to guard against a pass.

# Approaching Design as a Scientific Discipline

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**Abstract:** Scientific disciplines are those that have a few simple laws or rules that can be applied to solve a wide variety of problems in that discipline. Engineering design is, of course, a technological discipline. It relies on scientific findings and the scientific method. This paper examines the premise that design is governed by axioms and could be a scientific discipline. Scientific disciplines are easier to teach and to learn than experiential and artistic disciplines. The products of scientific disciplines should be easier to evaluate, and the development of solutions to problems in scientific disciplines should be more systematic than in experiential and artistic disciplines. Axiomatic Design (Suh 1990) utilizes two axioms with which, it is claimed, all good designs are consistent. This paper examines Suh's axioms, maximizing the independence of the functional elements and minimizing the information. If design can be a scientific discipline, then how can we know these are the correct axioms? Axioms cannot be proven, only disproven. Can there be sufficient conditions for the assuring that Suh's axioms are appropriate? Arguments about Axiomatic Design and domain of applicability of Axiomatic Design are examined. Suh's axioms are found to be consistent with the basic nature of design and transform engineering design into a scientific discipline.

**Keywords:** Axiomatic Design, Engineering Design, Science of Design, Measuring Design Value, Teaching Design.

## Introduction

The objective of this paper is to examine the premise that design is a scientific discipline, and, that as a scientific discipline, engineering design can be based on the axioms proposed by Suh (1990). Scientific disciplines in this sense are those that have a few, simple laws, or axioms, which can be applied to solve a wide variety of problems in that discipline.

If engineering design could be treated as a scientific discipline, governed by axioms, then the practice of engineering would be facilitated significantly. Axioms could be used for the evaluation of the quality of solutions to design problems. Scientific disciplines are easier to teach than experiential and artistic disciplines. The development of solutions to problems in scientific disciplines is more systematic and less subjective than in experiential and artistic disciplines.

The fundamental job of engineers is to design, i.e., create. Engineering design is about finding and developing new solutions to problems that face humanity. Scientists study things as they are and try to discover underlying principles that advance the understanding of the compact nature of the universe (Baum 2004). Scientists use a method of hypothesis formulation and testing. Engineers create new things for the service of humanity. Engineers use a process of design.

Engineers spend much of their training learning how to analyze (e.g., Norton 2003). The analysis is used, for example, to find the dimensions of a beam that will carry a certain load, or to find the size of an exchanger that will dissipate a certain amount of heat. In this way, part of engineering is an effort to predict the future, e.g., a bridge will support certain sized trucks and an exchanger will dissipate enough heat to maintain a certain temperature. Analysis is important because it provides predictions on the chance of success of designs. Analysis supports design, and it is a necessary component of design. However, analysis is not synthesis. It does not create. Design is synthesis. It creates. And it is the primary objective of engineering.

Nearly all things that humans encounter or interact with are designed: objects, devices, systems, organizations. Therefore, the methods by which things are designed impacts nearly everything in the human experience. Furthermore, it is proposed that all problems can be construed as engineering design problems. If this is true, then all problems could be addressed using the process of engineering design.

Engineering design is, of course, a technological discipline. Engineering design relies on scientific findings and the scientific method. Nonetheless, it does not necessarily follow that engineering design is itself a scientific discipline. However, if engineering design could be formulated as a scientific discipline, then it should be possible to make compelling arguments for the appropriateness of certain axioms, which would underlay the practice of engineering design.

Traditionally the design processes that have been taught in engineering schools are algorithmically based (e.g., Norton 2003). These kinds of design processes imply that good designs are

discernible because they result from the application of a good procedure. This basic concept of using a good procedure obviously has a lot of merit. However, it is not as useful or powerful as an understanding of design that is based on clear and simple criteria for quality, i.e., axioms, which can be applied regardless of what is being designed or what is known about the procedure that created the design.

## The Nature of Design Axioms

Axiomatic Design is distinguished from other engineering design methods by the utilization of two axioms. It is claimed that all good designs are consistent with these two axioms (Suh 1990). The first, or independence, axiom is: maximize the independence of the functional elements. This makes the design adjustable and controllable. The second, or information, axiom is: minimize the information content. This maximizes the probability of success. These two axioms form the basis for axiomatic design.

In order to apply the axioms, the design must be structured in a certain way, and decomposed appropriately. Of course, a procedure is required in order to achieve an appropriate decomposition consistent with the axioms. Therefore the practice of axiomatic design also relies on an algorithm. Finally, it is observed that the process of utilizing axiomatic design has three principle components: the axioms, the structure, and the procedure (Brown 2005).

The structure includes a lateral decomposition into domains, principally the functional and physical. The structure also includes a hierarchical decomposition, from abstract to specific, within the domains. The process includes a top down zigzagging between the domains, decomposing the design through levels of abstraction. The process also includes the compilation of the basic elements of the physical domain, which result from the decomposition, into a complete, integrated solution.

The axioms themselves are different from the procedure of applying the axioms, the practice of which has been called "axiomatic design". Clearly the axioms themselves are the most important component of axiomatic design, as they supply the basis for the procedure and its practice. Nonetheless, there are aspects of the procedure and practice of axiomatic design that have utility beyond the axioms themselves.

Axioms cannot be proven, only disproven. This work proposes logical arguments explaining why Suh's axioms and axiomatic design are a useful and natural foundation for the practice of engineering design. The practitioner decides if these arguments are compelling. In this endeavor, to argue in favor of the axioms, it should be sufficient to establish that there is a significant utility for the axioms and for the procedures for using axiomatic design to solve design problems. Suh's design axioms could be disproven by finding one good design that violates them, or one design that would be made better by ignoring them. In this regard, some types of apparent candidates for failures of axiomatic design will be discussed.

Design axioms are fundamentally different than scientific laws, in that scientific laws cannot be violated, e.g., all ordinary mechanical systems comply with Newton's laws. Designs do not have to comply with the axioms. Designs are human creations and humans can create poor designs. Therefore, designs can be created that do not comply with the axioms. However, the similarity between scientific laws and design axioms is that the basic hypothesis of axiomatic design is that the best design solutions are those that comply with Suh's axioms.

Newton studied physical systems, the motion of the planets and objects falling towards earth, to identify the commonalities and thereby discovered a more compact understanding of the physical universe (Gleick 2003). To develop the design axioms Suh studied designs to find what good designs had in common, and he transposed those commonalities to the axioms (Suh 1990). Suh's process for determining how to assess the value of designs early in the design process relied on examining successful designs whose success had been verified through their implementation. Suh's design axioms provide a more compact understanding of good design. Suh's design axioms should be as fundamental to the practice of engineering design as Newton's laws are to the understanding of mechanics.

## The Nature of Engineering Design

The human species is distinguished in part by its ability to create an abundance of new things. A basic ability to design appears to some degree to come naturally to many humans. Simple design problems are routinely solved by people intuitively. However, sufficiently intricate design problems may not be readily solved, or solved as well, using innate intuition. In these situations some process to extend intuitive design capabilities must be used. Design processes have been created to assist with design problems that are sufficiently large and intricate that they cannot be solved intuitively.

Engineering design is the process of discovering and describing solutions to problems that face people. Engineers design things that fulfill human needs. The first cannon of engineering ethics is to protect the health and welfare of the public. This cannon, it could be argued, obliges engineers to use their intellectual abilities to improve the human condition. Engineers are enjoined by the first cannon to mitigate things that would otherwise adversely impact people's health and welfare by designing devices and systems. Engineers also design things to be consumed for enjoyment beyond needs, things that people are willing to pay for. In any event, the solutions to design problems have value. The process of designing creates value.

Engineering Design is functionally oriented. A

design solution is intended to fulfill certain functions. These functions are the design goals, or the functional requirements. Success of a design is defined by the ability of the product that is designed to fulfill these functions. It is in this success that the design attains its value. The actual value to humanity, however, is only realized when the product described by the design is realized. All projects above some simple level of intricacy require a conscience design effort to have any reasonable chance of success.

This design effort is a linking, or mapping, of the functional requirements (FRs) to the physical attributes, or design parameters (DPs) that fulfill or accomplish the FRs. This mapping process between functional and physical spaces, or domains, is fundamental to the nature of design. The manifestation in the physical domain is what is often referred to as the design. The functional space could be said to contain the design intent and the physical space contains the design solution.

## Creating Value by Thinking

Essentially, an engineer creates value by thinking. Engineering design involves conceiving and detailing solutions to problems and then communicating the solutions, so that they can be implemented. The act of the creation of the designed product can be said to be separate from engineering design. The final product of an engineer's efforts is the communication of the design solution. This is the description of the product, and not the product itself. The engineer's contribution to the product is thought, in the embodiment of a design solution.

Thought has been said to be all about semantics (Baum 2004). Thought in engineering design, at the least, requires semantics. Thought in design is about finding physical solutions to functional requirements. The thought itself is not physical and therefore must be symbolic. In solving analytical problems, engineers are comfortable reducing the problem to mathematical symbols and finding the solution symbolically.

The product of the design process is symbolic, usually a set of drawings or instructions. The semantics and pragmatics of the symbols in mechanical drawings are precisely defined by engineering committees like ASME Y14 and ISO TC213. These committees, however, do not address the semantics that can be used in the process of discovering elements of the physical domain that can fulfill the FRs.

The elements in the functional domain, as defined by human (or customer) needs, and the physical domain can be described symbolically (Suh 1990). These symbols can be manipulated and solutions can be analyzed for their ability to succeed.

Success is evaluated by the compliance with the axioms. The degree to which designs can satisfy the axioms indicates their chance of success. Initially compliance with the axioms can be evaluated early in the conceptual stages of the design, long before the physical elements of the design are transposed into the precise language of engineering drawings.

## Design Metrics

The fact that design creates value, suggests that a method for quantitatively assessing designs is by the value they create. This implies that some designs are certifiably better than others. Without the axioms, assessment of designs by the value they create might have to wait until the value is realized, i.e., after the transformation of the design into a useful product.

Lord Kelvin is supposed to have written that measurement, i.e., the ability to express something in numbers, is a requirement for improvement and management. Management of the design process is impossible without metrics that can be used during the process. This can be difficult, especially in the conceptual stage. Without the axioms, progress can be measured by steps through the algorithmic process. However, as discussed above, this lacks a metric for quality.

There is important value in being able to evaluate value of designs early in the design process. This would be to measure the level of certainty that given DPs will be able to fulfill the FRs of the design. This is assessed by the compliance with the axioms. This compliance can be evaluated in the conceptual stages of the design process, allowing design solutions to be compared without making larger investments in the detailing of designs or in modeling and prototyping.

## Adjustability and Controllability – Axiom One: Maximize Independence

Two features that appear to be common to all designs and design activities are: the ability to adjust to changes, and the ability to control the output of the designed product.

In a large sense, designed products need to adapt to the ubiquitous change that is a feature of our universe. In a smaller sense, even a designed component, which is relatively removed from external changes during operation, was, during the design process, adapted to its particular environment or conditions. These conditions might include, for example, the loads and temperatures in which it must operate. During the analysis that is part of the design process, that environment becomes better known and defined. The size, shape and materials of the designed product are better defined or adapted. The knowledge of some aspect of the environment might change during the design process and some corresponding parameter in the design of the component may also change, in order to adapt to the change in the knowledge of conditions. In any event, adaptability is a common feature to design.

In that the product of the design is attempting to accomplish some function, some measure of control

is required. The success of the designed product is determined by the success in fulfilling the FRs. Determination of success implies the ability to measure the degree of fulfillment of the FRs. Too much or too little, or maybe both, of whatever the FR requires, would indicate failure of the design. This means that there is some kind of functional tolerance that indicates the target for success. Achieving a tolerance implies a need to control the quantities specified in the tolerance.

A fundamental feature of effective control strategy is the ability to control the functional elements independently. One of the principles of developing the functional requirements is a definition that specifies that function requirements are things that need to be controlled separately. Lack of independence means that in attempting to adjust one parameter, for example DPi, to satisfy FRi, another function, maybe FRj, is taken out of tolerance. Then some other parameter, maybe DPj, needs to be adjusted to bring FRj back into tolerance. In a fully coupled design this could take FRi back out of tolerance, requiring another adjustment to DPi. This iteration process might converge by bringing both FRi and FRj into tolerance, and then again, it might not. At best, these kinds of iterations take time to reach a solution, and they do not add value. Axiom one addresses this problem.

Axiom one states that good designs maximize the independence of the functional elements. This makes the design adjustable and controllable and avoids unintended consequences.

## Simplicity for Success – Axiom Two: Minimize Information

In science, when considering competing hypotheses that can explain the observed data, the simplest explanation is chosen. This is referred to as the principle of Occam's razor or lex parsimoniae. Similarly, in engineering, when considering competing designs that are equivalently able to fulfill the customer needs, the simplest should be chosen.

In order to apply a criterion of greatest simplicity, simplicity should be defined. In science the simplicity of the hypothesis is indicated by succinctness and the number of assumptions. In engineering, the simplicity of the design could be indicated by the independence and the information. Suh's two axioms could be said to be a decomposition of simplicity into more basic elements.

The probability of success in the design, i.e. fulfilling the FRs, is improved by simplicity. An important part of simplicity is ease in adjustment, and axiom one addresses that. Axiom one should be applied before axiom two (Suh 1990).

Axiom two addresses the probability of success directly. Information content (I) is defined as the log of the inverse of the probability (p) (Suh (1990):

$$I = \ln (1/p) \qquad (1)$$

If the design is not adjustable, then the probability of success is low. Axiom one could be viewed as addressing a component of achieving success - a component that is special enough to deserve its own axiom. In practice, many advantageous applications of axiom one can be found.

Simplicity is an indication of the certainty of success. Complexity, the opposite of simplicity, is therefore an indication of the uncertainty in achieving success – the greater the uncertainty the greater the complexity. Minimizing the complexity therefore maximizes the probability of success.

Uncontrollable and unpredictable elements cannot be completely designed out of any system. For example, the universe has significant chaotic components, like the weather, and all manufacturing processes have some variance. Axiom two addresses robustness in design by selecting solutions that are less sensitive to chaotic conditions and variance. Products of design should show a consistency, or symmetry, in fulfilling the FRs with respect to changes.

## Consideration of Apparent Failure Candidates

The author is unaware of any failure of the axioms to indicate the best design solution. This experience includes more than a quarter of a century of using axiomatic design, as well as teaching it to engineering students and design practitioners. During this time everyone has been invited to find violations of the axioms. No one has found a design that would be better if it violated the axioms. Some people, however, have struggled with the process of axiomatic design.

There have been failures in use of axiomatic design. These arise principally through difficulties in finding good decompositions. The failure of the practitioner to be able to develop a good decomposition is not a failure of the axioms. Poor decompositions are an impediment to utilization of axiomatic design, and need to be addressed separately.

Axiom one has been misconstrued to mean that each function needs a separate component. In fact, many functions can be fulfilled with the same component. DPs can be physically integrated on one part, as long as the functions can still be fulfilled separately (Suh 1990). Physical integration of DPs tends to reduce the information content in manufacturing and can reduce the information content in the product.

Most failure candidates are poor designs resulting from an axiomatic design process. These usually result from failures to appropriately define the FRs. A design can be no better than the FRs (Suh 1990). The FRs need to translate the customer needs into elements that can be used in the design process.

In the design process, time needs to be allocated to the development of FRs, particularly at the highest levels. Everyone involved in the design needs to

understand the value in defining good FRs at the highest levels and devote resources appropriately. Poor choices of FRs at the highest levels cannot be corrected at the lower levels. The design process defines its own metrics for success: the FRs. The FRs define what the design is supposed to do. The design solution is developed to fulfill the FRs.

## Usefulness and Axiomatic Design

Usefulness in the design process is something that will assist designers in arriving at a better design in a shorter time. A legitimate concern with axiomatic design is the time and effort required to reach a design solution. Even though it might be agreed that the application of some systems could result in a better design, the extra burden in terms of time and effort required for their application needs to be justifiable.

The practice of axiomatic design has been found to significantly reduce the time required to find design solutions, when compared to the system that it replaced. This reduction is despite what might be construed as the extra effort required for the axiomatic design process. This raises the question: how could this process, with the extra burden of applying the axioms and developing the requisite structure to apply them, also reach a better solution in less time than other methods that don't have that burden? To address this question, the design process must be decomposed into value adding steps. Then, the process for achieving these steps needs to be examined.

If the design process is only evaluated after a detailed design is completed, perhaps through a number of specific reviews, the process of getting to the details will be difficult to evaluate. It is useful to have some progress metrics during the design process.

Value added during the design process could be defined as reaching consensus among the stakeholders on certain intermediate decisions that are essential for arriving at the detailed, final design. In this way, a value stream can be mapped and non-value adding processes recognized.

Early in the design process, the links to the final design may seem distant. This is similar to evaluating the early moves in chess. Even when checkmate or the capture of a major piece may be remote and uncertain, some moves are better than others. It is not enough to make a decision early in the process of developing the design, there must be some method of evaluation of the quality of that decision. The axioms can supply that evaluation. Axiomatic design supposes that the best design will be that which maximizes the independence then minimizes the information. If this is true, then appropriate application of the axioms can assure that the best design decisions are being made.

The development of the design solution in axiomatic design process suggests some metrics. The zigzagging decomposition is a top-down development from abstract concepts to specifics. At each level, the FRs are developed from the customer needs, or from an appropriate decomposition of the next higher level FRs. The DPs that can satisfy the FRs at that level of abstraction are selected and then compliance with the axioms is tested. As discussed above, the obvious metrics for design progress are: the level of abstraction to which the design solution has been decomposed, the degree of independence, and the information content.

The use of metrics in assessing the quality of design options for comparison can help to build consensus on design options, moving the decision making process from argument to analysis. The axioms and structure supply rules that are used in making design decisions. This kind of rule-based decision making thereby eliminates some non-productive discussions.

Communication of the design intent is also important in building consensus. The association of FRs and DPs in the process of axiomatic design clearly specifies the intent at every level of abstraction in the design.

When the independence is incomplete, the knowledge of unintended interactions indicates orders of development that that avoid unnecessary iterations, and the extent of the influence of changes in the design.

It is proposed that the systematic decomposition and application of the axioms reduces the time to produce a completed design, because it organizes the design process appropriately, focuses discussions on essential elements, reduces the time to make design decisions, and eliminates unnecessary iterations in the design process.

## Conclusions

Five conclusions can be drawn from this work:

- Engineering design can be approached as a scientific discipline.
- Suh's axioms have a natural basis in engineering design.
- The process of axiomatic design can find the best design solutions for a given set of functional requirements.
- The practice of axiomatic design can provide progress metrics for value added during the development of design solutions.
- Axiomatic design provides useful design procedures.

## Acknowledgements

This paper is dedicated to Nam P. Suh, the father of axiomatic design, and an extraordinary human being. The author gratefully acknowledges the kindness of Kate Thompson in selecting me to give this keynote as well as her valuable discussions and editing, which have improved this work.

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# Axiomatic Design for Creativity, Sustainability, and Industry 4.0

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**Abstract.** This paper discusses how to foster creativity and sustainability during Axiomatic Design processes, including Industry 4.0 as an example application. Creativity is generating valuable, new ideas. Innovation is making new ideas viable. This paper explains how AD theory and methods can improve the selection process in evolution-inspired creativity for formulating functional requirements and generating and selecting design parameters. FR formulation is a key to creating value in design solutions. No design solution can be better than its FRs. The FRs must capture the true, underlying essence of customer needs. In addition, an FR must define the solution space appropriately, so that all the best DP candidates are included. Suh's axioms are used to select the single best DPs from the candidates. In AD, viability is established systematically during the axiomatic decomposition and the physical integration processes. Methods for detecting poor design thinking are presented. Metrics and tests for evaluating FRs' facility for creativity and innovation are proposed. Techniques for improving FRs are proposed, decomposed, and reviewed for their compliance with the axioms.

## 1 Introduction

### 1.1 Objective and rationale

The objective of this paper is to show how creativity and sustainability can be systematically integrated into design processes using Axiomatic Design (AD) methods and applied to Industry 4.0 (I4.0). Creativity is the generation of valuable, new ideas. Innovation, often a companion term to creativity, is making new ideas viable. AD methods apply Suh's axioms to a systematic design process [1] that can make creative ideas feasible. Sustainability is essential to viability and value in engineering.

This approach is important because creativity and sustainability are essential to the development of good design solutions, although details of how to systematically include these things in the design process are not well recognized. Previous industrial revolutions have created many sustainability challenges. Perhaps I4.0 provides an opportunity for remaking production systems and initiating a green industrial revolution [2].

This is also important because not many engineers are familiar with ethics and design theories, at least formally. Unfortunately, few engineers, engineering educators, engineering administrators, and engineering students know even the first canon of engineering ethics. In addition, few engineers can name any design theories or formal design methods, nor can they appreciate how these can be systematically integrated with creativity and sustainability. The teaching of ethics in engineering schools is often limited to the minimum instruction for meeting accreditation criteria. Climate change has become widely recognized as a global crisis. Design solutions must be consistent with sustainability, if something of life as it has been known on this planet can be saved. Ethics are integral to viability and integrity in engineering design solutions.

The first canon of engineering ethics states that the safety, health, and welfare of the public must be held paramount [3]. If someone does not hold these three things of greatest value, then that individual is not doing engineering and not behaving as an engineer. Because sustainability is essential to the safety, health, and welfare of the public and the planet we all live on, it is inseparable from the first cannon. Fostering sustainability in design practices is especially important, because the future of life on this planet depends on it.

As a design theory, AD is exceptional because it establishes axioms for testing the viability of all kinds of design solutions and disciplines. Suh's design axioms elevate design to a scientific discipline, because it consists of a few simple, self-consistent principles that can be applied to solve a wide variety of problems [1].

Conventionally I4.0 includes applying recent technological developments to manufacturing. These developments include, artificial intelligence, Internet of Things (IoT), cyber physical production systems, and collaborative robotics. I4.0 can include more than that. Industry uses significant amounts of energy and produces waste in many forms. I4.0 should, through newly

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available technologies and improved productivity, address sustainability.

Systematically integrating creativity and sustainability is important because design is transdisciplinary and ubiquitous. Everything people consciously interact with can involve design. For most people, design would be a secondary discipline. Everyone who seeks solutions to problems, plans or creates, anything from fine arts to zoological theories, is designing. Suh's two axioms can be applied to solve problems in everyone's primary discipline, a wide variety. Like all scientific laws, these two axioms exploit the basic, compact nature of the universe for anybody designing anything. Discussions about how to integrate ethics, creativity, innovation, and sustainability into AD are important to advancing the practice of engineering design.

A systematic approach to creativity, innovation, and ethics would be important for students and teachers of design, technology, and engineering, at all levels, from kindergarten to post doc. Currently, scientific theories and methods are introduced to students at a young age. It is indisputably important that everyone understands science, even though relatively few people become scientists. Design theories and methods are not systematically introduced to students at any age, even to engineering students. Nonetheless, everyone solves problems; therefore, we are all designers. We could all benefit from an understanding of design theory and methods. We should all embrace ethics and sustainability.

### 1.2 State of the Art

There is, of course, considerable literature on creativity and sustainability. This literature is found in many fields, including philosophy and many scientific and engineering disciplines. These concepts have been included in AD processes and discussed in a much narrower part of the literature. This part of the literature is briefly reviewed here.

According to Suh (1990, p. 9) [1], creative processes synthesize new ideas, or solutions, without prior examples, i.e., prior art. He notes two processes in design: creative and analytical. Analytical processes evaluate ideas for making design decisions, i.e., selection among ideas. AD theory states that good design solutions comply with Suh's axioms, first maintaining independence of the functional elements, and second minimizing the information content [1]. The theory states that the axioms are used in the analyses to select the best design solutions from all the candidate ideas.

In the AD method, design ideas, or candidate solutions, are tested against Suh's axioms at each level of abstraction, in systematic, zig-zagging decompositions, from abstract to detailed, in three or four domains. The domains are identified as customer, functional, physical, and process domains. These contain customer needs (CNs), functional requirements (FRs), design parameters (DPs), and process variables (PVs), respectively. The DPs are the physical part of the design solution. A complete design solution includes physical integration, uniting the detailed DPs into a physical model, which complies with the axioms [1].

Park [4] discussed teaching conceptual design using AD. He used open-ended design projects, done in groups. His description did not address specifics about how to develop concepts. Most decisions were made by intuitive heuristics, experience, and brainstorming. The conclusion was modest, declaring AD to be good for an objective or scientific method. Mathematical formulae were not used, and the experience of the instructor was emphasized.

Foley and Harðardóttir [5] studied manifestations of artistic creativity developed in a multidisciplinary collaboration with AD. Engineering and artistic disciplines communicate through an abstract analysis of the artistic needs, defined in terms of feelings and experiences, which become FRs. DPs are proposed, and the opinion of the collaborating artist is the test for fulfillment of the FR. The key is communication through sufficiently abstract expression of the FRs.

Four steps to the design process were presented by Suh and Sekimoto in 1990 [6], then paraphrased by Kim and Cochran in 2000 [7]. They are further paraphrased below, to be cast in the imperative for use later in this paper as FRs in a new design problem.

**Table 1.** Four steps in the design process.

| Design process |
|---|
| (1) Define required functions (FRs) to solve the problems posed by the customer needs (CNs). |
| (2) Create ideas for solutions (DPs), maybe several candidates, to fulfill each FR. |
| (3) Select the best candidates for solutions. |
| (4) Check complete solutions against CNs. |

Suh and Sekimoto [6] note that each step can require iteration. These iterations can include going back to step one to redefine FRs, and to step two to create new ideas, modifying proposed solutions. Importantly, Suh and Sekimoto [6] also note that, ultimately, design solutions are represented by design equations, which relate functions and solutions. The fulfillment of each FR by a DP, and the possible influences of others, is represented mathematically. Kim and Cochran [7] state that AD covers just the third step in Table 1, where Suh's axioms discern good and bad design solutions. They go on to state that AD suffers from a lack of systematic approaches to finding satisfactory candidate DPs.

The creativity step is discussed in C-K theory [8] and TRIZ [9], both of which have been integrated with AD. TRIZ proposes forty kinds of inventive concepts, gleaned from examining patents. C-K theory builds on design spaces of concepts and knowledge, exploring and expanding each to accommodate new ideas, which require new knowledge.

The cross-disciplinary journal, *Sustainability*, decomposes sustainability into four elements: environmental, cultural, economic, and social. All four of these can be included in design problems. Brown [3]

formulates two basic FRs for AD of manufacturing processes, one to add value and the other to minimize cost. Cost includes the cost of sustainability, which is part of the first canon of engineering ethics. To hold paramount the safety, health, and welfare of the public, engineers certainly must address the environment. The cultural, economic, and social aspects of sustainability should also be included.

Beng and Omar [10] take a more detailed view about sustainability, specific to engineering design. They note three key areas that must be considered for developing sustainable products: end-of-life management, green supply chains, and sustainable manufacturing. These address the environmental component. Proper training in design for sustainability, along with a global perspective, are required for engineers. Sustainability problems require multiscale solutions, seamlessly integrated into design processes. AD processes have advantages. The domains in AD distinguish objectives or intent (FRs) from solutions and means (DPs and PVs). Decompositions in AD, from abstract concepts to detailed solutions, enable the development of multiscale solutions that consistently embody principles for sustainability. Beng and Omar [10] conclude that including FRs for end-of-life management at the highest levels leads to design alternatives that can be profitable. The information axiom can address multi-criteria problems for green supplier selection. They proposed a decomposition for sustainable product development with rules for decision-making in their three key areas.

Elaborating on integrating a manufacturing component into sustainability and AD processes, Poser and Li [11] note that clean processing can be either as a constraint (C) or an FR-DP pair. Constraints are favored, because they avoid producing anything unwanted, rather than having to find a solution to dealing with unwanted byproducts. They use toxins as an example, not producing them as a constraint, is preferable to removing them from waste streams, which requires an FR-DP pair. Taking a similar approach, Lee and Badrul [12] compare material-removal processes. Rather than Cs, they define tolerances for energy use in the FRs and waste products in material-removal processes. They calculate the information content based on the probability of achieving the tolerances needed to select the best material-removal process.

Brown [13] writes that I4.0 is often defined by the solutions it offers, i.e., DPs, including, cyber-physical production systems, IoT, collaborative robots, and artificial intelligence. An issue for AD of I4.0 is to understand the kinds of design problems, i.e., FRs, that are solved best by these DPs. According to Suh [14] an FR0, the top FR, for enterprises can be provide adequate return on investment (ROI). This suggests that FR children should be minimize investment and maximize return. However, these FRs only work when there are systems for maximizing or minimizing that can be DPs. The DPs for I4.0 solutions should be considered broadly, beyond the new, high-tech solutions promoted with I4.0, because other solutions might require less investment [13] and offer adequate return.

I4.0 raises new social, cultural, and economic sustainability issues. In his novel *Player Piano*, Kurt Vonnegut describes a highly automated and somewhat disturbing new world [15]. This fictional society is confronted with new industrial revolutions that have similarities to I4.0. Vonnegut discusses the societal, cultural, and economic consequences of the devaluation of human thought by thinking machines. Vonnegut did not, however, anticipate AD.

Potentially, the technological innovations associated with I4.0 should create increasing global wealth while, with appropriate economic and social incentives, mitigating climate change by improving energy efficiency and reducing waste [2]. Indeed, I4.0 has recently been cited as promoting energy efficiency, contributing to mitigation of climate change, and promoting sustainable energy use by industry [16].

### 1.3 Approach

Suppose that any problem can be cast as an engineering design problem. Further suppose that AD is the best approach to solving engineering design problems. Then AD is the best approach to solving any problem. The approach here consists of appropriately decomposing the problem according to procedures used in AD [17].

Here, as opposed to Park [4], quantification and formulae are discussed. In addition, abstracting the needs into appropriately broad FRs is used to provide a space for the design solution that encompasses creative solutions, as with Foley and Harðardóttir [5].

One problem examined here relates to creativity in AD. Considering the four steps in the design process (Table 1), AD addresses the third, an analysis for selection of solutions from candidates. Steps one and two appear to be the most applicable for fostering creativity. Therefore, AD decomposition is applied here to solving the problems posed by the first two steps.

The second problem to be considered using an AD decomposition here relates to include sustainability into the solution of design problems. The four components of sustainability can make good CNs. However, they appear to overlap, meaning that they are not mutually exclusive, and, therefore, do not adapt well directly as FRs [18], although they could become constraints.

Finally, the problem is to understand how creativity and sustainability can be integrated into an approach to AD for I4.0. Freedom and dignity are elements of culture and society that must be sustained and included in the CNs. If I4.0 diminishes these things and serves to enrich further those who are already wealthy, then the economic component of sustainability will have failed as well. Just as the first industrial revolutions served to free people from much of the labor required for manufacturing, I4.0 has the potential to free people from mundane thought processes. The intellectual resources that are freed by I4.0 should be applied to enhancing our human experience. I4.0 improvements can be tied to mitigating climate change naturally, because I4.0 should seek improved ROI through increased efficiency and productivity, rather than

increased wealth generation through increased energy use as in the first industrial revolutions.

Biologically inspired creativity is considered. Ideas are like genes, because they can be combined in different ways to create different solutions. To describe creativity, Suh [1] uses the term synthesis, which literally means combining ideas. Genetic algorithms and evolutionary computation can be used to create design solutions, by forming exhaustive combinations of selected elements and testing according to quantitative criteria, in order to determine the best [19-21]. Pollan [22] writes about substance-assisted mutation of ideas to assist in creativity, which would be followed by natural selection for survival of viable ideas.

## 2 Methods

AD decomposition processes are applied systematically for including and fostering creativity in AD, and for integrating sustainability into AD processes. Finally, AD decomposition processes are applied to I4.0, to make it part of a green industrial revolution. These are rather abstract high-level decompositions, intended to keep a broad domain of applicability. This section presents the general methods for these decompositions in such situations. The following section, "3 Results", shows the content of the decompositions and explains how the choices were made.

### 2.1 Collecting and understanding CNs

The AD decomposition begins by collecting the CNs, which must include the needs of all stakeholders [23]. Then, an effort must be made to understand the CNs, so that the correct problem can be solved.

Proponents of innovation at a technical university encourage students to interview customers. This is a good idea, of course. However, the more important lesson for the students is how to derive the fundamental needs from all the CNs. These need to be understood adequately so that the best FRs can be formulated.

Henry Ford is supposed to have said that if he had asked people what they wanted; they would have said a faster horse. The implication is that the need was for transportation and that Ford understood this. People acquired large fortunes by fulfilling this need for transportation with cars. The further implication is that the automobile has been a great success. However, consider the fact that, worldwide, about one and a quarter million people are killed every year in traffic accidents [24]. In the UK alone the cost of health problems attributed to cars is about 6 billion pounds per year [25]. This would appear not to be sustainable, yet it has been sustained. Furthermore, Henry Ford is widely admired as a successful entrepreneur.

The CNs for economic sustainability through increased efficiencies can lead to I4.0 solutions that can help to reverse climate change by using less energy and creating less waste.

Allowing individuals to amass great wealth should not be a measure of success if it includes unpaid damage to the safety and health of the public. It is not ethical. It is not sustainable. It leads to social instability. Clearly, there must be more to assessing CNs than commercial success. It is difficult to see how the appearance of success, based on wealth, can change in the absence of systems for assigning costs to the industries that generate them. Economic sustainability cannot be independent of the sustainability of the environment, society, and culture. These are all coupled in fact and must be coupled in actual function as well. The unintended consequences of addressing one problem and creating others is a violation of Suh's axiom one.

### 2.2 Developing FRs and Cs

FR0 and constraints (Cs) are developed from the CNs [1, 26]. There are opportunities for creativity in design processes by collecting CNs from all the stakeholders. Fundamental needs of stated CNs should be understood and appropriately formulated into FRs.

The technique of "five whys", used by Toyota [27] to identify the root causes of a problem in production, could be applied to CNs, in order to identify and understand the fundamental needs. With this understanding, a more useful FR for fostering creative solutions might be formulated.

If it is not possible to think of several DPs that can satisfy an FR, then maybe the FR is too confining and should be changed. The region between the customer and physical spaces is where the functional space is located. This region can be a continuum. The closer FRs are to the physical space, the smaller is the solution space for that FR. The more physical the FR is, the less solution-neutral it is, and the smaller the solution space for that FR.

FRs must be developed to leave the largest possible space for the physical solution. This is intended to allow for new solution ideas. This is another opportunity for creativity. An FR that is lacking in solution neutrality can constrain the solution unnecessarily. If the interpretation of the potential consumer's self-assessed need for a faster horse had been taken literally, then the problem was to develop faster horses. This was the response for centuries previously.

The internal combustion engine and the development of metals' technologies facilitated a new, disruptive solution to the transportation problem, if it was recognized as such, and an enlarged solution space could be created. Traditional FRs had to be adjusted to exploit new solution spaces. I4.0 can be seen similarly. New production technologies can enlarge solution spaces. FRs must be adjusted to go beyond the spaces that only allowed solutions enabled by previous technologies. FRs that might once not have been considered because they were thought to be unrealistic, could now be achievable.

In the decomposition, FR child elements must be collectively exhaustive and mutually exclusive (CEME) decompositions of their parents [17]. CEME decompositions comply with Suh's axioms. If the children are not mutually exclusive with respect to each other, then independence is not maintained. If children are not collectively exhaustive with respect to the parent, then

some part of the solution has been lost, the probability of success is diminished, and the information content is not minimized, violating Suh's axiom two. Themes, like energy and time, decomposed into kinds of energy and segmentations of time, can help to verify that decompositions are CEME.

One difference between FRs and Cs is that FRs need to be mutually exclusive with respect to each other, whereas Cs might not be separable from at least some of the FRs.

Another difference is that FRs require DPs to fulfill them. To keep the solution simple, FRs should be kept to the minimum required to satisfy the CNs. Therefore, Cs are favored over FRs for meeting CNs, however Cs restrict the solution space. If the solution space becomes over-constrained, then a solution might not exist in this space.

Clearly, it is better not to create waste as a byproduct, which favors dealing with the environmental aspects of sustainability as constraints. However, this constraint might overly restrict the process options, possibly leaving no options that do not violate the axioms. Then, the treatment of the waste could be added as another FR.

### 2.3 Synthesizing, selecting DPs, and decomposition

Synthesizing DPs to fulfill FRs is an important creative step. A method for solving seemingly unsolvable large problems is to decompose them into many, solvable smaller problems, then to integrate these into the solution of the larger problem.

Zigzagging decomposition between FRs and DPs at progressively more detailed levels should continue until the solution is obvious [1]. At the upper levels, with less detail, DPs might just restate FRs. If FRs are "provide X", DPs can be systems, devices, or mechanisms that provide X. This might seem to lack value, except that it helps to categorize and define independent branches that follow specific themes. Qualifiers, like mechanical or electrical, specify and better define the theme. Different themes and qualifiers can be attempted. Genetic algorithms [21] can be used to attempt and test all the combinations against the constraints and Suh's first axiom, then rank them with Suh's second axiom, if there are enough options to merit this approach.

To solve design problems, eventually solution specifics are needed at the lower levels. Zigzagging decomposition can progress to levels where solutions to detailed FRs are obvious. This way, decompositions foster creativity by building frameworks for many small creative steps, rather than fewer, huge creative leaps. This is good, when it works. However, decomposition processes do not always arrive at this happy conclusion.

Perhaps the solution does not exist yet. A solution could require new technology. The decomposition should assist in identifying missing components. The new technology might be developed by further decomposition and understanding the problem at fundamental levels.

Decomposition processes can restrict solution spaces. To foster creativity, solution spaces should be kept as large as possible. At each step, it is good to have several candidate DPs for each FR. If not, then maybe themes and qualifiers on parent DPs should change, and maybe FRs should be changed. This might be required for synthesizing appropriate DPs.

Once several candidates have been identified, then the task is to name the best choice. Cs should be applied first, which might eliminate some candidates. If Cs eliminate too many or all DP candidates, then this could be an over-constrained approach to the problem. Maybe a new decomposition theme should be found. To enlarge the design space, some constraints could be changed to FRs. After applying Cs, Suh's axioms are applied in the usual manner to remaining candidate DPs, in order to select the best one. In the process of applying axiom one, the specific detailed solutions at the lower level need to be inherited to the upper levels, with the resulting coupling thereby reflected at these upper levels [28].

In summary, creativity is fostered by decomposing until the solution is obvious. This should provide small creative steps, which should have simple, obvious candidate solutions. The best DPs are reduced by applying the Cs and axiom one, and then ranking by axiom two. This process can combine ideas, like genes, at the most detailed level, which blend, or integrate, functionally, or are synthesized into larger creative solutions. Genetic algorithms can be used to investigate different functional combinations of detailed genes of ideas from different branches [19-21]. These new functional configurations solve larger problems at higher levels of abstraction. The next step is the physical integration of detailed DPs into a complete solution.

### 2.4 Physical Integration of the DPs

Physical integration can be another opportunity for creativity in the configuration of individual DPs into complete entities. Physical integration does not need to follow the path of the functional-physical decomposition, and generally does not. Certain physical elements need to be materially connected or supporting to achieve functionality. DPs should be combined into sub-systems and systems to achieve desired functionalities. This process resembles the decomposition process, except in reverse. Multiple physical integration configurations can be considered. Again, genetic algorithms and an evolutionary approach to creativity [19-21] can be used to evaluate all the combinations, by applying constraints and Suh's first axiom, possibly eliminating some combinations, and then by ranking those remaining with Suh's axiom two, to select the best integration solution.

A physical integration matrix, showing physical DP-DP interactions, is useful to evaluate Suh's first axiom and avoid unwanted interactions. It can also assure that there are interactions where they are required.

### 2.5 Sustainability and I4.0

Metrics for the success of I4.0-related FRs need to be based on improved efficiencies in energy utilization, productivity, and waste reduction. Implementation of new

technologies in I4.0 cannot be sustainable if the metrics are based on shortsighted energy use and waste production. The earth is reaching the limits of its tolerance for non-sustainable activities. For survival, society needs to impose costs on energy use and waste production that are commensurate with the actual damage to the environment. I4.0 needs to rise to this challenge of producing wealth while preserving health. I4.0 needs to include product design, in order to design products for production and systems for use by I4.0. The technological resources of I4.0 can be used to address all products, processes, transportation, communication, and systems. This could make it a system for sustainability for all human activities.

### 2.6 Representation of Design Solutions and Metrics

Methods need to include design-solution representations and metrics. Without a representation, there is no design. Without a measurement of the level of success of a design solution, according to Lord Kelvin's legendary pronouncement about measurement, design solutions cannot be improved. Representations of design solutions commonly include information required to manufacture solution, a solid model with dimensions and tolerances, and a bill of materials. The design intent, FRs, is not commonly included in design solution representations. This makes improvement unnecessarily uncertain and replete with unintended consequences. Unless design intents are linked to design solutions in representations, changes in the design solution introduce uncertainty in amended functions. FRs record design intent and are a necessary pre-physical step in design thinking. Complete design representations could also include evidence of creative struggles by capturing all candidate DPs and the reasons for not selecting them. Evidence of creativity, innovation, ethics, and sustainability should be evident in complete representations of design solutions.

## 3 Results

The result of creative, sustainable AD is the beginning of a decomposition to address the fundamental needs. The fundamental customer, or societal, need is for sustaining the environment, cultures, economies, and societies. There are undesirable aspects of these entities that should be improved, rather than sustained. "Sustain" might not be the best term; however, these improvements and phraseology are left for discussion in other forums.

Table 2 shows the initial draft of a decomposition, intended for designing decompositions to produce creative design solutions consistent with sustainability through I4.0. Novice users of AD often mistakenly begin with an FR0 to design some artifact, when what they mean to do is to design something that will function like that artifact, e.g., a bicycle. The FR0 in Table 2. is intentionally about design. DP0 is a design system. The children in Table 2 follows the theme outlined in Table 1, and they are collectively exhaustive in that regard. There are more details in Table 2, including the developments in the methods section for creativity.

At this level the proposed DPs are appropriately abstract. Critically speaking, they might appear to add little to a design solution. Nonetheless, they clearly define specific, mutually exclusive components of the solution.

**Table 2.** Upper-level decomposition of design for sustainability (I4.0).

| FR | DP |
|---|---|
| **FR0 Design for sustainability (I4.0)** | **DP0 Creative design system for sustainability** |
| FR1 Develop appropriate CNs | DP1 Fundamental CN development method |
| FR2 Constitute suitable Cs | DP2 Suitable C constituting method |
| FR3 Formulate satisfactory FRs | DP3 FR formulation for large solution spaces |
| FR4 Create ideas for solutions, DPs | DP4 Creative solutions for multiple DPs (iterate 1) |
| FR5 Select the best solutions, DPs | DP5 Selection method on Cs and Suh's axioms |
| FR6 Integrate DPs for complete solution | DP6 Physical integration method |

The decomposition is full lower-triangular, with sequential coupling, because successful completion of each FR depends on satisfying the previous one [29]. Usually there is no need to iterate if the correct sequence is followed. Here, iteration is required if solution spaces are small, because CNs and FRs might not be sufficiently fundamental, or Cs are overly restrictive. The need to iterate is indicated by the inability to create multiple solutions.

Metrics and tests for evaluating the degree of success in fulfilling FRs should be selected when FRs are defined. Only with metrics can a DP be fully and truly evaluated for its appropriateness. Complete evaluations of DPs should include quantitative indications of sustainability, as well as of their ability to fulfill FRs. In this regard, there could be two components and two sorts of design equations containing DPs, one each for functionality and sustainability. Metrics can also be used to test for CEME in decomposition equations.

## 4 Discussion

AD provides several possibilities for fostering creativity, the synthesis of good, new ideas. Creative opportunities begin by collecting CNs from all the stakeholders [1, 23].

CNs require fundamental interpretation to formulate FRs and Cs [1, 26]. A design solution can be no better than the FRs [1]. Because of this, FRs are key to optimizing value in design solutions. FRs must capture the true, underlying essence of CNs. Five whys, as used in troubleshooting in lean manufacturing, can be used for getting to the root of design problems and assisting in creative FR formulation. FRs can be thought of as existing

on a continuum that extends from the CNs to the DPs. Moving FRs away from physical solutions and toward fundamental CNs can help to enlarge the design solution space. Decompositions should be pursued to finer and finer details, until the creative steps are sufficiently small to be obvious. A good decomposition process is essential in this approach to creativity.

The fundamental nature of Suh's axioms are to establish viability through a kind of functional modeling or testing for good solutions, i.e., adjustable, controllable, avoiding unintended consequences, and robust. Innovation can be advanced by application of Suh's axioms to functional-physical decompositions and physical integrations.

Sustainability can be derived naturally from the first canon of ethics for engineers: hold paramount the safety, health, and welfare of the public. Importantly, I4.0 suggests new technologies that can fulfill FRs that previously could not be done, because there were no physical solutions available. Properly executed, I4.0 provides opportunities for achieving sustainability in a fractal-like manner. This means that, at all levels of manufacturing processes and systems, there is a self-similar pattern of using new technologies to improve productivity and reduce waste. I4.0 cannot truly address sustainability while fostering the current trend in the US of concentrating more wealth in the hands of fewer people. This has led to unethical management of wealth and power by climate change deniers, who ignore sustainability.

I4.0 has the potential to eliminate jobs that underutilize intellectual capacity. With proper training, newly available intellectual capacity can be used to advance sustainability and reverse climate change. High-quality education needs to be universally available. Particularly in the US, industry uses engineers, extracting value from their work, without contributing to the high cost of their undergraduate education. Foreign-educated engineers can enter the US workforce, with documentation for legal immigration, without having to repay the crushing debt acquired by many US engineers during their undergraduate education. Access to education should be based only on aptitude and not on ability to pay. Well-trained, ethical engineers are required to reverse climate change. Any society that discriminates on anything besides aptitude will underperform. All human potential should be brought to the rescue of the environment and the enhancement of sustainability. Systems that permit amassing of wealth at the cost of sustainability should not be allowed.

Complete representations of design solutions should include design intent, metrics, and logical paths leading to creative solutions. These records are more elaborate that those currently in common use. They provide for more sophisticated assessments of the design solutions and also can facilitate creativity and advance sustainability by providing guidance for future design development through strong knowledge management. Steps in the decomposition should be retained for future reference, including CNs, FRs, candidate DPs and the reason for their rejection or retention. Industry is losing value in the design process by missing this opportunity.

## 5 Conclusions

1. AD provides several possibilities for fostering creativity, including understanding fundamental needs of the customers and stakeholders, defining satisfactory FRs, and creating multiple DP candidates for selection. The latter can be achieved by decomposing until the solution is obvious.
2. Viability for advancing innovation can be achieved by application of Suh's axioms to functional-physical decompositions and physical integrations.
3. Properly executed, Industry 4.0 provides opportunities for achieving sustainability in a fractal-like, self-similar, multiscale manner.
4. Representations of design solutions, including FRs for design intent, metrics for FRs and DPS, and logical paths leading to creative solutions, with alternative DPs, can advance sustainability and provide valuable guidance for future design works. Design software should include these features.
5. Definitions of Industry 4.0 should include FRs, i.e., design intent, emphasizing its potential to address sustainability, including engineering ethics, the safety, health and welfare of the public, and climate change

This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No. 734713.

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# Day 3: Room V111-112-113 / V114 / V115 / V116 / V119

| Day 3 – 29 Jan 2021 | | | |
|---|---|---|---|
| **Timetable** | **Type of Course** | **Title Course** | **Speakers** |
| 9:00 - 9:45 | **Advanced topic / Paper discussion (5)** | Demonstration of fixation effect during generation of creative ideas from fundamental experimentation approach to applied experimentations. | Justitne Boudier |
| 9:45 - 10:30 | **Advanced topic / Paper discussion (6)** | Design, Creativity and design Theory | Gaetano Cascini |
| 10:30 - 11:00 | **Break** | | |
| 11:00 – 11:45 | **Breakout groups (4/5)** | Exploring your thesis with Design Theory | Professorial College |
| 11:45 - 12:30 | **Breakout groups (5/5)** | Exploring your thesis with Design Theory | Professorial College |
| 12:30 - 14:00 | **Lunch** | | |
| 14:00 – 15:00 | **Advanced topic / Paper discussion (7)** | Conjunctions of Design and Automated Search in Digital Innovation | Albrecht Fritzsche |
| 15:00 – 16:00 | **Publishing in design theory** | Room V115 | Yoram Reich (RED) |

**Justine Boudier**

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Main research interests: psychology of creativity, creative leadership

**Title of the Presentation:**

Modelling and experimenting defixating leaders with design theories

**Synopsis:**

In this presentation, we will discuss how the interaction between design theories an cognitive psychology can help us modelling and experimenting defixators leaders. Indeed, ideas generation can be blocked by a cognitive bias, preventing individuals to generate creative ideas: they are fixed on few uncreative path of solutions. However, it has been showed that leaders can act to defixate their teams and help them overcoming this fixation effect.
After presenting the challenges of theoretical and methodological analyses of fixation effect in creativity, we will highlight how design theory can be used to build theoretical model, generate hypotheses ang then experiment defixating leaders.

**Main References**

Ezzat, H., Camarda, A., Cassotti, M., Agogué, M., Houdé, O., Weil, B., & Masson, P. L. (2017). How minimal executive feedback influences creative idea generation. *PLOS ONE*, *12*(6), e0180458. https://doi.org/10.1371/journal.pone.0180458

**Further readings:**

Agogué, M., Kazakçi, A., Hatchuel, A., Masson, P. L., Weil, B., Poirel, N., & Cassotti, M. (2013). The Impact of Type of Examples on Originality: Explaining Fixation and Stimulation Effects. *The Journal of Creative Behavior*, *48*(1), 1–12. https://doi.org/10.1002/jocb.37

Cassotti, M., Camarda, A., Poirel, N., Houdé, O., & Agogué, M. (2016). Fixation effect in creative ideas generation: Opposite impacts of example in children and adults. *Thinking Skills and Creativity*, *19*, 146–152. https://doi.org/10.1016/j.tsc.2015.10.008

Ezzat, H., Agogué, M., Le Masson, P., Weil, B., & Cassotti, M. (2018). Specificity and Abstraction of Examples: Opposite Effects on Fixation for Creative Ideation—Ezzat—- The Journal of Creative Behavior—Wiley Online Library. *Journal of Creative Behavior*, *0*(0), 1–8. https://doi.org/10.1002/jocb.349

# How minimal executive feedback influences creative idea generation

**Article** *in* PLoS ONE · June 2017

DOI: 10.1371/journal.pone.0180458



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RESEARCH ARTICLE

# How minimal executive feedback influences creative idea generation

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**Citation:** Ezzat H, Camarda A, Cassotti M, Agogué M, Houdé O, Weil B, et al. (2017) How minimal executive feedback influences creative idea generation. PLoS ONE 12(6): e0180458. https://doi.org/10.1371/journal.pone.0180458

**Editor:** Mark A. Runco, University of Georgia, UNITED STATES

**Received:** January 18, 2017

**Accepted:** June 15, 2017

**Published:** June 29, 2017



**Data Availability Statement:** All relevant data are within the paper and its Supporting Information files.

**Funding:** This work was supported by the French National Research Agency (project ANR-13-SOIN-0004-02 IDéfixE). The funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

**Competing interests:** The authors have declared that no competing interests exist.

## Abstract

The fixation effect is known as one of the most dominant of the cognitive biases against creativity and limits individuals' creative capacities in contexts of idea generation. Numerous techniques and tools have been established to help overcome these cognitive biases in various disciplines ranging from neuroscience to design sciences. Several works in the developmental cognitive sciences have discussed the importance of inhibitory control and have argued that individuals must first inhibit the spontaneous ideas that come to their mind so that they can generate creative solutions to problems. In line with the above discussions, in the present study, we performed an experiment on one hundred undergraduates from the Faculty of Psychology at Paris Descartes University, in which we investigated a minimal executive feedback-based learning process that helps individuals inhibit intuitive paths to solutions and then gradually drive their ideation paths toward creativity. Our results provide new insights into novel forms of creative leadership for idea generation.

## Introduction

Fixation effects [1] have always been recognized as among one of the most important barriers to 7creativity. Over the past decades, numerous cognitive science studies have underlined the obstructive function against creative ideation of the spontaneous activation of known solutions and knowledge in individuals' minds. These studies have demonstrated that previously acquired knowledge in individuals' minds fixate them and consequently restrain their aptitude for the generation of creative ideas [2].

Numerous psychologists have been interested in demonstrating fixation effects [1, 3, 4]. One classical task illustrating such effects is the "two cord problem" [3]. Participants are given two cords that are tied to the ceiling and a pair of pliers. The participants are then asked to tie the free ends of these two cords together with the knowledge that the cords are short and cannot be held in the hands at the same time in a manner in which one could easily tie them

together. One solution to this problem is to simply tie the pliers to one of the cords to form a pendulum that will swing to enable the reaching of the second cord. In this experiment, most participants are fixated on their proper knowledge of pliers and their conventional uses and do not consider the alternative use of the pliers to form a pendulum.

Over the past years, the field of design science has been very useful to the modeling and precise identification of these cognitive biases to creativity. Indeed, Concept-Knowledge (C-K) theory [5] is well renowned as a tool to not only force designers' reasoning to succeed in overcoming fixation effects [6] but is also recognized to aid the generation of ideas that are inside or outside of existing paradigms [7]. This theory distinguishes between a fixation path that is based on the spontaneous activation of knowledge (inside fixation) and an expansive path that is based on the activation of less accessible knowledge (outside fixation) and consequently offers a method to characterize different paths of solutions in addition to the knowledge bases associated with these solutions.

Using this C-K-based cartography of solutions, interdisciplinary studies that mix human cognition with design theory have been able to develop smart lock-in methodologies to overcome fixation effects. These studies have demonstrated the stimulating role of expansive examples, i.e., ideas and solutions that are outside fixation effects, in elevating the creative generation capacities of individuals [8]. The authors utilized a classical creative ideation task that consists of proposing the maximum number of solutions to ensure that a hen's egg dropped from a height of ten meters does not break. Using an existing database of solutions created over the last five years [8], the authors revealed that 81% of the solutions belonged to three categories of "restrictive" solutions within the fixation path (i.e., damping the shock, slowing the fall, and protecting the egg). However, only 19% of the solutions were "expansive" solutions, i.e., solutions that were outside of the fixation path (for instance, solutions implemented before and after the fall, the use of a living device, and the use of the intrinsic properties of the environment). The authors then demonstrated that, when the participants were given a creative example (outside the fixation path) prior the task, they proposed more original solutions. Similarly, these studies also emphasized the obstructive role of restrictive examples, i.e., ideas and solutions that were inside the fixation path, to the creative generation process. These studies were performed with participants with different backgrounds (i.e., students, psychologists, engineers, and designers) [9] and different ages [10, 11] and have noticeably confirmed the negative role of restrictive examples (i.e., examples within the fixation path) on the fluency and originality of the proposed solutions to the same creative task.

Developmental psychology theorists have analyzed the problem at the reasoning level and realized that thinking outside the box may also require first resisting what is inside the box. Indeed, these scholars have investigated the problem of cognitive biases at the reasoning processes level and have underscored the critical role that could be played by inhibitory control of the fast and intuitive system of reasoning in overcoming heuristics in certain cases [12–14]. Based on the dual-process theory of reasoning comprising both an intuitive system (system 1) and an analytic system (system 2) [15, 16], these authors have proposed a third system termed "cognitive inhibition" (system 3) [13]. The latter system plays the role of inhibiting the fast and intuitive system (system 1) to release the slow and analytic system (system 2). Along these specific lines, recent works have linked these above-mentioned findings with the context of cognitive biases to creativity. Considering that the difficulty in generating creative ideas might result from individuals' failures to inhibit spontaneous responses that come to mind and lead them to fixate on certain knowledge, these authors have proposed an analogical model of reasoning in creativity situations that they termed the "dual-process model of creativity" [17]. Similarly, these works argue that the abilities of individuals to resist the spontaneous activation of design

heuristics by inhibiting inappropriate ideas is a crucial factor in the generation of creative ideas [18–20].

In line with the above ideas, in the current paper, we propose a learning process that can be implemented to guide individuals' systems of reasoning for creativity. More precisely, with the help of design theories, such as the C-K theory [21], in the present study, we analyzed the roles of feedback processes in i) the inhibition of obvious solutions to a particular creativity task and ii) the gradual forcing of individuals' reasoning to explore and activate novel and creative ideas and solutions to problems.

The concept of feedback is widely used in different domains, and its definition varies significantly depending on discipline [22]. Feedback can be described as the control of a process based on its results, i.e., the output of an action is returned to modify the subsequent action. Feedback is an efficient instrument in the control and regulation of individuals' performance in real-time and is extensively used in learning processes.

Few studies have been devoted to the relationship between feedback and creativity. Most researchers have examined feedback from a very broad perspective. These researchers have investigated the influence of evaluative information on creative performance and argued that it could have a strong influence on enhancing creative processes [23]. Indeed, these studies have underscored the importance of being exposed to others' ideas and perspectives in the stimulation of the generation of creative ideas. Other studies have noted that feedback can significantly help to regulate individuals' creative performances [24]. Moreover, other findings have argued that delivering negative and controlling feedback to individuals can damage their creative performance, and in contrast, the delivery of constructive or developmental feedback can exert a positive influence on creativity [24–28].

In the domain of reasoning, Moutier and Houdé [29–31] developed a training paradigm that involves explicit executive feedback regarding various reasoning biases. Using a classical pre-test/training/post-test design, the efficiency of this training procedure is indexed by comparing the post-test performance with the performance in the control training with the logic that the latter only differs due to the absence of executive feedback. Therefore, the specificity of the executive training lies in the presence of executive feedback, such as "we're falling into a trap! (. . .)" or "The goal here is not to fall into the trap (. . .)". The words "not to fall into the trap" in this training procedure are introduced to provoke a tendency to reject the biased strategy. Although the reasoning biases were found to be very high, the results revealed that only the executive training improved the subjects' metacognitive ability to overcome classical reasoning biases, such as the conjunction fallacy and the matching bias, during deductive reasoning [29]. In other words, this study emphasized the near transfer effect by confirming that the executive training could be transferred to structurally similar tasks. This experimental design was also applied during a brain imaging study, and the results revealed a reconfiguration of neural activity that correlated with the near executive transfer effect in the domain of deductive reasoning [32]. The results revealed clear shift in neural activity from the posterior part of the brain prior to executive training (i.e., when the participants' responses were biased by the use of system 1) to the prefrontal portion after training (i.e., when they became able to inhibit the system 1 intuitive response and provide the correct answer via the use of system 2). Altogether, these findings demonstrated that executive feedback can provoke the inhibition of strongly intuitive wrong answers [33] and provided the first insights into the neuropedagogy of reasoning [34].

Despite the contributions made to the literature of creativity and the importance of studying the influence of feedback on ideation from this above-mentioned relatively broad perspective, to the best of our knowledge, no previous studies have focused on the influence of executive

feedbacks from a deeper perspective from which minimal feedback might control individuals' ideations during real-time processes to guide them outside of fixation.

In the present study, we propose a minimal executive feedback-based learning model that could guide individuals' idea generation paths whether inside fixation, i.e., a conceptual space associated with the fixation effect, or in expansion, i.e., a conceptual space associated with concepts outside of fixation. In other words, we were interested in modeling a learning process that can guide individuals' ideation paths toward certain types of ideas and solutions whether they are restrictive, i.e., do not change an object's definition or attributes, or expansive, i.e., transform an object's definition and identity [8].

Therefore, the aim of the present study was to examine how minimal executive feedback influences individual ideation in real-time. To achieve this aim, participants were asked to solve a creative task (i.e., the egg task) and were provided with minimal executive feedback after each generated solution.

Critically, the executive feedback was either congruent or incongruent with the creative aim of the egg task. In the congruent executive feedback condition, the feedback suggested that the participants "search for another path" when the proposed solution belonged to the fixation path and "continue in this path" when the solution belonged to the expansive path. In the incongruent feedback condition, the feedback suggested that the participants "continue in this path" when the proposed solution belonged to the fixation path and "search for another path" when the solution belong to the expansive path.

We reasoned that if creative idea generation requires the inhibition of the intuitive path to the solution that leads to the fixation effect, as posited by the dual process model of creativity and the C-K theory of design, then the executive feedback should have affect the participants' performances in the egg task relative to a control condition that involved no instructive feedback (i.e., "I confirm the receipt of your idea"). Specifically, the congruent executive feedback should improve performance by facilitating the inhibition of ideas within fixation and stimulating the exploration of ideas in expansion, whereas the incongruent executive feedback should impair performance by interfering with the inhibition of uncreative ideas that lead to fixation and stimulating the exploration of ideas within the fixation path.

## Experiment 1

### Method

**Participants.** Sixty undergraduates from Paris Descartes University participated in this study (32 men, mean age = 20.5 years, SD = 2.62). Each participant was randomly assigned to one of the three following experimental conditions: congruent executive feedback (n = 20; 13 men), incongruent executive feedback (n = 20; 12 men), and a control group that received neutral feedback (n = 20; 7 men). ANOVA and chi-squared analyses indicated that the mean ages ($F(1,57) < 1$) and gender distributions ($\chi 2 = 1.70$, $p = 0.12$) did not differ significantly between the groups. All the participants provided written consent and were tested in accordance with national and international norms governing the use of human research participants. The institution that granted permission for the following experiments is the faculty of psychology of the University of Paris Descartes.

**Procedure.** The participants sat alone in an experimental room in front of a computer and were asked to wait for the experimenter to contact them via a text (written) chat conversation using Skype. The experimenter initiated the chat conversation and provided the following initial brief to the subject: "design a process that allows by which a hen's egg that is dropped from a height of ten meters does not break". Each subject was then instructed by the experimenter to write down, in the chat conversation, the maximum number of original

ideas they could generate to solve this problem. The task duration was set to 10 minutes per participant.

Using an existing database of solutions that was collected over the last five years [8], two experimenters were trained before the experiment to identify whether a generated idea belonged to the fixation paths (which included damping the shock, slowing the fall, and protecting the egg) or were outside of those paths (for instance, interventions implemented before or after the fall, the use of a living device, the use of the intrinsic properties of the environment, etc.). Table 1 lists the categories of solutions to the hen's egg task according to the database.

The participants in the control group received neutral feedback that simply acknowledged the reception of an idea generated by the subordinate and awaited the next idea. For the participants in the congruent executive feedback group, if the generated idea was in the fixation path, the feedback provided was "search for another path"; in contrast, if the generated idea was in the expansion path, the provided feedback was "continue in this path". In contrast to the congruent executive feedback group, for the participants in the incongruent executive feedback group, if the generated idea was in the expansion path, the provided feedback was "search for another path"; in contrast, if the generated idea was in the fixation path, the provided feedback was "continue in this path".

**Results.** To examine whether the numbers of proposed solutions (i.e., fluency) within the fixation path (fixation) and outside the fixation path (expansivity) varied according to the experimental conditions, we conducted a repeated-measures analysis of variance (ANOVA) with the experimental condition (congruent; control and incongruent) as a between-subjects factor and the category of solution (fixation vs. expansion) as a within-subjects factor, and we used the partial eta squared ($\eta_p^2$) and Cohen's d to examine the effect size.

This analysis revealed a main effect of the solution category ($F(2, 57) = 9.49$, $p < .005$, $\eta_p^2 = .14$, Power = .86) that indicated that the participants provided more solutions in the fixation path than in the expansion path. There was no main effect of the experimental condition ($F(2, 57) < 1$). However, there was a significant experimental condition x category of solution interaction ($F(2,57) = 10.4$, $p < 0.001$, $\eta_p^2 = .27$, Power = .99, see Fig 1A).

One-tailed planned comparisons were corrected with a Holm–Bonferroni procedure for analyses of the number of solutions within the fixation path and within the expansion path separately. Results revealed no significant difference between the number of solution within the fixation path in the control group (M = 6.75, SD = 3.85) and those in the congruent group (M = 5.15, SD = 2.06; $F(1/57) = 2.42$, $p_{corr} = .12$, d = .52). In addition, there was no significant difference between the number of solution within the fixation path in the incongruent group (M = 7.85, SD = 3.56) compared to the control group (M = 6.75, SD = 3.85; $F(1/57) = 1.14$,

**Table 1. Categories of solutions to the egg task [8].**

| Categories | Example of Solutions |
|---|---|
| Damping the shock | Place a mattress at the reception |
| Protecting the egg | Pack the egg with bubble wrap |
| Slowing the fall | Hang the egg to a parachute |
| Interrupting the fall | Catch the egg with a net |
| Acting before the fall | Drop the egg at a height of 11 m |
| Acting after the fall | Replace the broken egg with an unbroken one |
| Using a living device | Train an eagle to take down the egg |
| Modifying the properties of the egg | Freezing the egg |
| Using the natural properties of the egg | Drop the egg on its most robust axis |
| Using the properties of the environment | Drop the egg at zero gravity |

https://doi.org/10.1371/journal.pone.0180458.t001

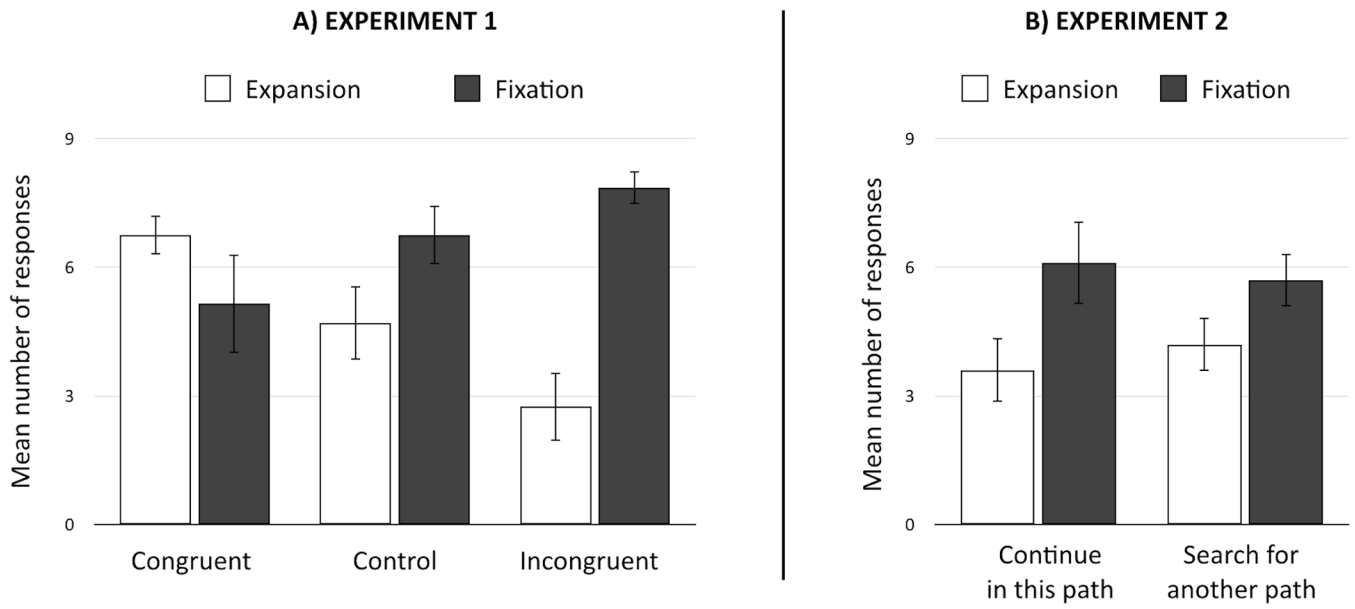


**Fig 1.** Mean number of solutions according to the experimental condition (A: Congruent/Control/Incongruent; B: Continue in this path/Search for another path) and the type of solution (Expansion/Fixation).

https://doi.org/10.1371/journal.pone.0180458.g001

$p_{corr}$ = .29, d = .30). Interestingly, participants proposed fewer solutions within the fixation path in the congruent group (M = 5.15, SD = 2.06) than participants in the incongruent group (M = 7.85, SD = 3.56; F(1/57) = 6.89, $p_{corr}$ = .03, d = .92)

Critically, the participants in the control group (M = 4.7, SD = 3.04) proposed fewer solutions in the expansive path than did those in the congruent group (M = 6.75, SD = 5.12; F(1/57) = 3.88, $p_{corr}$ = .05, d = .49). Additionally, the participants in the control group (M = 4.7, SD = 3.04) proposed more solutions in the expansive path than did those in the incongruent group (M = 2.75, SD = 1.71; F(1/57) = 3.51, $p_{corr}$ = .032, d = .79). Finally, the participants in the congruent group (M = 4.7, SD = 3.04) proposed more solutions in the expansive path (M = 6.75, SD = 5.12) than did those in the incongruent group (M = 2.75, SD = 1.71; F(1/57) = 14.79, $p_{corr}$ = .0005, d = .1.05).

**Discussion.** The aim of the present study was to examine the influence of a minimal executive feedback-based learning process on the performance of an individual ideation task in real-time to explore how such feedback could guide individuals' creative reasoning. Three major findings emerged from this investigation as follows: 1) congruent executive feedback increases individuals' idea generation within the expansive path; 2) incongruent executive feedback has the opposite effect; and 3) critically, incongruent executive feedback had a weaker effect on creative performance than did congruent executive feedback.

Our results demonstrated that our minimal executive feedback-based learning process could be implemented to gradually force individuals' reasoning to explore and activate novel and creative ideas and solutions to problems. This stimulatory effect of the congruent executive feedback extends previous findings regarding the influence of training paradigms involving explicit executive feedback on various reasoning biases [29–31]. Indeed, these studies have consistently reported that executive training can greatly improve individuals' metacognitive abilities to overcome classical reasoning biases, such as the conjunction fallacy and the matching bias, during deductive reasoning. Moreover, our results are also coherent with those of previous studies that have been performed on the neuropedagogy of reasoning [34] and

demonstrated that minimal executive feedback can clearly provoke the inhibition of strongly intuitive wrong answers [33].

While our findings support the dual systems model of creativity, one limitation of the present study might be that depending on the experimental condition, participants might simply interpret the feedback "search for another path" and "continue in this path" as meaning something along the lines of "be more creative" and "be less creative" respectively. Given that the same feedback were used in both the congruent and the incongruent conditions this alternative explanation seems less likely. Nevertheless, to determine whether the stimulation effect of the congruent feedback condition arise from the interpretation of the instruction "search for another path" as "be more creative" and the instruction "continue in this path" as "be less creative", the influence of these specific feedback regardless of the response provided by the participant were examined in a second experiment. We reasoned that if participants interpret the instructions as mentioned below, they should generate more creative responses when they receive "search for another path" feedback after each generated solution, and fewer creative responses when they receive "continue in this path" feedback.

## Experiment 2

### Method

**Participants.** Forty undergraduates from Paris Descartes University participated in this study (19 men, mean age = 21.25 years, SD = 3.71). Each participant was randomly assigned to one of the two following experimental conditions: the "search for another path" condition (n = 20; 10 men), and the "continue in this path" condition. ANOVA and chi-squared analyses indicated that the mean ages ($F(1, 38) < 1$) and gender distributions ($\chi 2 = 0.10$, $p = 0.75$) did not differ significantly between the groups. All the participants provided written consent and were tested in accordance with national and international norms governing the use of human research participants.

**Procedure.** The procedure was similar to the one used in experiment 1 except the nature of feedback provided during the egg task. Indeed, for the participants in the "search for another path" group, the feedback provided after the generation of each idea was "search for another path" regardless of the type of idea proposed. In contrast, for the participants in the "continue in this path" group, the feedback provided was "continue in this path" regardless the idea proposed.

**Results and discussion.** To examine whether the numbers of proposed solutions (i.e., fluency) within the fixation path (fixation) and outside the fixation path (expansivity) varied according to the experimental conditions, we conducted a repeated-measures analysis of variance (ANOVA) with the experimental condition (search for another path vs. continue in this path) as a between-subjects factor and the category of solution (fixation vs. expansion) as a within-subjects factor, and we used the partial eta squared ($\eta_p^2$) and Cohen's d to examine the effect size.

This analysis revealed a main effect of the solution category ($F(1, 38) = 5.53$, $p = .02$, $\eta_p^2 = .13$, Power = .63, see Fig 1B) that indicated that the participants provided more solutions in the fixation path (M = 5.9, SD = 3.03) than in the expansion path (M = 3.9, SD = 3.59). There was no main effect of the experimental condition ($F(1, 38) < 1$), nor significant experimental condition x category of solution interaction ($F(1,38) < 1$). These absence of effect suggested that participants do not interpret the feedback "search for another path" as meaning to be more creative and confirmed that congruent executive feedback are required to positively influence creative ideas generation.

## General discussion

The findings of the present study showing that congruent executive feedbacks increase creative ideas generation are in accordance with those of previous studies in that feedbacks in general, and more precisely executive feedbacks, can strongly influence and regulate the creative performances of individuals [24]. Moreover, these findings are consistent with those of the majority of studies that have argued that the delivery of constructive feedback can positively influence creativity [25–28] and extend previous findings by demonstrating that such constructive feedbacks can assume simpler forms, such as elementary and minimal guiding instructions (e.g., instructions such as "continue in this path" and "search for another path"). Such feedback requires minimal effort from the instructor given that he has the capacity to approximately recognize the frontier between fixation and expansion.

Our results also confirmed that fixation effects do exist in creativity and that these effects that tend to focus on usual and common ideas to solve a problem (i.e., ideas belonging to the fixation path) can be reinforced using incongruent executive feedback. This result is in accordance with those of previous studies that have demonstrated the strength of the fixation effect in creative idea generation and the difficulties of redirecting an individual toward expansive reasoning (2; 7–11).

## Conclusions

In conclusion, our results clearly demonstrate that incongruent feedback reduces individuals' creative performances by decreasing the generation of ideas outside fixation and increasing the generation of ideas inside fixation. In contrast, congruent feedback enhances individuals' creative performances by increasing the generation of ideas outside fixation and decreasing the generation of ideas inside fixation. Finally, the process of the generation of ideas inside fixation is much more free-flowing that the process of the generation of ideas outside fixation, which confirms that the generation of ideas inside fixation requires less effort and is more automatic and intuitive according dual-process model of creativity. As such, it is notable that these results provide new insight into research on the modeling of new forms of creative leadership from a learning perspective in which creative leaders could have an influence on their followers' creativity level based on cognitive approaches to idea generation that involves influencing the followers' cognitive reasoning rather than influencing other aspects related to creativity (such as intrinsic or extrinsic motivation, creativity-supportive environment, etc.) [35, 36].

## Supporting information

**S1 File. Supporting information files.**
(XLSX)

## Acknowledgments

This research is part of a project IDéfixE of the French National Research Agency (project ANR-13-SOIN-0004-02 IDéfixE).

## Author Contributions

**Conceptualization:** Hicham Ezzat, Mathieu Cassotti, Marine Agogué, Benoît Weil, Pascal Le Masson.

**Data curation:** Hicham Ezzat, Mathieu Cassotti.

**Formal analysis:** Hicham Ezzat, Mathieu Cassotti.

**Funding acquisition:** Mathieu Cassotti.

**Investigation:** Hicham Ezzat.

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**Software:** Hicham Ezzat, Anaëlle Camarda.

**Supervision:** Mathieu Cassotti, Marine Agogué, Benoît Weil, Pascal Le Masson.

**Validation:** Hicham Ezzat, Mathieu Cassotti, Marine Agogué, Olivier Houdé, Benoît Weil, Pascal Le Masson.

**Visualization:** Hicham Ezzat, Anaëlle Camarda.

**Writing – original draft:** Hicham Ezzat, Mathieu Cassotti.

**Writing – review & editing:** Hicham Ezzat, Mathieu Cassotti.

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## Gaetano CASCINI

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Main research interests: methods and technologies supporting design creativity and innovation, design cognition and its experimental investigation.

**Title of the Presentation:**

Design, creativity and innovation

**Synopsis:**

Innovation is nurtured by the interplay between research and creativity. Often innovation starts from the discoveries produced through research. Sometimes creative imagination produces visions that determine the agenda of research.
We will discuss the dimensions of design creativity and its potential role to foster innovation, as well as what design theory can do to enhance creative skills and individuals' talent.

**Main References**

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Research in Engineering Design (2019) 30:133–153
https://doi.org/10.1007/s00163-018-0299-2

ORIGINAL PAPER

# Sources of creativity stimulation for designing the next generation of technical systems: correlations with R&D designers' performance

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Received: 1 May 2017 / Revised: 3 September 2018 / Accepted: 1 October 2018 / Published online: 5 December 2018


**Abstract**
This paper presents the outcomes of an exploratory research to clarify the performance of R&D designers when involved in design task for the ideation of the next generation of a technical system. The research aims also at clarifying if creative stimuli play a role in supporting ideation after idea generativity decreases because of natural exhaustion or the emergence of fixation. The effect of precedents (singular as patents, and structural as technology evolution trends), as well as design strategies (in the form of a design procedure for inventive problem solving) on idea generation, is compared by means of an experiment involving 24 R&D Iranian engineers. Precedents demonstrated to be more effective than design strategies in supporting productivity in idea generation, while generally they are not effective enough to support the generation of candidate ideas for the next generation of a technical system with a robust repeatability. The main recorded lacks depend on the capabilities of creative stimuli to support the generation of novel ideas, as they are generally effective in providing good results with reference to technical plausibility and relevance for a target audience. The results of the experiment are also discussed with reference to the efficiency of the design process (number of generated ideas per time unit). The outcomes of such studies, as part of a broader research objective, serve as input to support the development of a serious game to support R&D engineers to face design tasks for the next generation of technical systems with higher motivation and engagement, providing them with an improved design experience.

**Keywords** Technological shifts · Radical innovation · Novelty · Creative stimuli · Design precedent · Design strategies · Design models

## 1 Introduction

Designing the next generation of technical systems (NGTS) is a very specific and crucial design task, as its output (design concepts, proposals), once engineered, can change the market interest and, therefore, undermine the other companies' products position in the market. The cyclonic vacuum cleaner (with less dusty air to the surrounding), as well as the automated vacuum cleaner (which detects rubbish), is an example of attempts of companies to substitute existing vacuum cleaners with the next generation of such products and become market leaders. Technological product innovations account for one-fourth to one-third of organizational growth (Zirger and Maidique 1990; Lee and Sukoco 2011). Innovation helps firms to grow and compete. Radical innovation, defined as fundamental changes for new products as revolutionary technology shifts that also meets the appreciation of the market (Ettlie et al. 1984; Dewar and Dutton 1986; Song and Thieme 2009), provides firms with better position and performance outcomes (Germain 1996). Despite there is no explicit mention to "design for NGTS" in design literature, the generation of ideas determining a technological shift that also have high innovation potential is a very specific design task that becomes particularly crucial in any industrial context, especially where the competition is based on the acceptance of new products by the market. A relatively wide thread of scientific literature, therefore, focused the attention on what can stimulate the generation of extremely novel ideas of high quality (e.g.: Heylingen et al. 2007; Fu et al. 2013).

In this context, R&D Engineers are expected to be the most active players in design for NGTS tasks and they should be put in the condition to fluently generate ideas that have

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good chances of becoming a radical innovation. Nevertheless, most of the existing literature that deals with inspiration to generate novel and high-quality ideas explored the effects of creative stimulation with experiments that just involved students (e.g. Zahner et al. 2010; Tseng et al. 2008; Doboli and Umbarkar 2014), highlighting that tailored methods and tools for R&D engineers to face this highly creative design activity are still lacking. With a more professional-oriented perspective, one of the closest contributions available in the literature deals with the application of solution-oriented technology forecasting techniques (Cascini 2012), despite this is originally a more strategy-oriented activity. Moreover, that contribution presents methods and tools that aim at supporting professionals, but it also claims that professionals find some of the proposed approaches too complex or too rigid for application (e.g. ARIZ, as for Altshuller 1988) and there is no new experimental evidence calling into question this statement.

In fact, academically developed methods and tools to improve design effectiveness and efficiency are just slowly penetrating industrial practice (e.g.: McMahon et al. 2016; Fiorineschi et al. 2018), because designers and R&D engineers usually find them too rigid and time consuming for their consolidated ad-hoc, unsystematic (Cross 2001) and opportunistic way of designing (Visser 1990).

According to the above-mentioned aspects, which limit the engagement and the proficient creative stimulation of professionals, it appears reasonable to leverage designers' creativity by exploiting different modalities of interaction with design methods and tools. The authors believe that the introduction of a ludic dimension in the design process, within this kind of open-ended task, can help R&D engineers and designers to overcome some of the barriers hindering the adoption of design methods and tools and facilitate the engagement among colleagues. Serious game, in fact, is riding high as a market trend and some items for leveraging creativity with appropriate stimuli, through game-based communication channels, are already available for purchase on e-marketplaces, e.g. https://goo.gl/n1JUZF.

This research is a first step towards the development of a serious game to support R&D engineers in designing the next generation of a technical system. Two main elements are needed to design a serious game and help gamers to develop their skills: a right balance between the active involvement of owned skills and, through learning-by-playing, the development of new ones. In details, this paper focuses on the effects that different creative stimuli have over a collaborative ideation process for the NTGS, as a refined version of them will be tuned for the game mechanics (to be completed, based on the outcomes of this research).

The paper has the following structure: first, an overview of the research methodology to frame the paper content with respect to the research activity. Then, previous findings in design, cognition and creativity literature are presented and discussed to develop both a preliminary set of tailored creative stimuli and appropriate metrics for the assessment of candidate ideas for the next generation of technical systems. Section 5 deals with the setting, the design task and other details of the experiments that involved 24 R&D Engineers, together with the rules for data acquisition, assessment and processing. The results of the experiments and a discussion of the main evidences, with reference to previous findings are, respectively, in Sects. 6 and 7, just before the conclusions.

## 2 Research questions and methodological approach

As briefly mentioned in the introduction, this paper aims at informing the early stages of the development of a serious game to support R&D engineers in conceiving the NGTS. The IDEF0 (IDEF is for Integrated DEFinition, a family of modelling techniques—http://www.idef.com) diagram in Fig. 1 presents an overview of the research methodology. Within IDEF0 models, each box of the diagram represents an activity that is detailed with brief textual description (middle of the box) and labelled with a letter and a number (lower right corner, e.g. A1).

Consistently with such modelling notation, in Fig. 1 every activity carried out along the research aims at transforming an input into an output. Inputs and outputs are represented as arrows that are, respectively, incoming (left side of boxes) and outgoing (right). Arrows that enter boxes from below represent the resources required to carry out that action. With reference to Fig. 1, these resources can be human (e.g. experiment manager and participants), tangible (e.g. pen and paper used for the experiment) or intangible (as the contents for creative stimulation, despite they were represented on paper).

Arrows that enter boxes from top represent the set of rules which controls the execution of the activity. In Fig. 1, these rules correspond to the metrics for the assessment of candidate NGTS ideas as well as the definition of experimental groups and data acquisition protocol.

It is worth noticing that outputs of an activity can be used as inputs for next ones (e.g. the design task defined in box A1 is the input for the execution of the design session, as for box A3), but also as resources (this is the case of creative stimuli generated after the activity labelled A2) as well as controls (i.e. the rules used to run the activities, as for two of the outputs of A1, which are control for A3 and A4).

Due to the scarcity of information concerning the outcomes of the ideation process for this specific kind of design task, this paper more specifically aims at gathering initial insights about ideation performance in such a

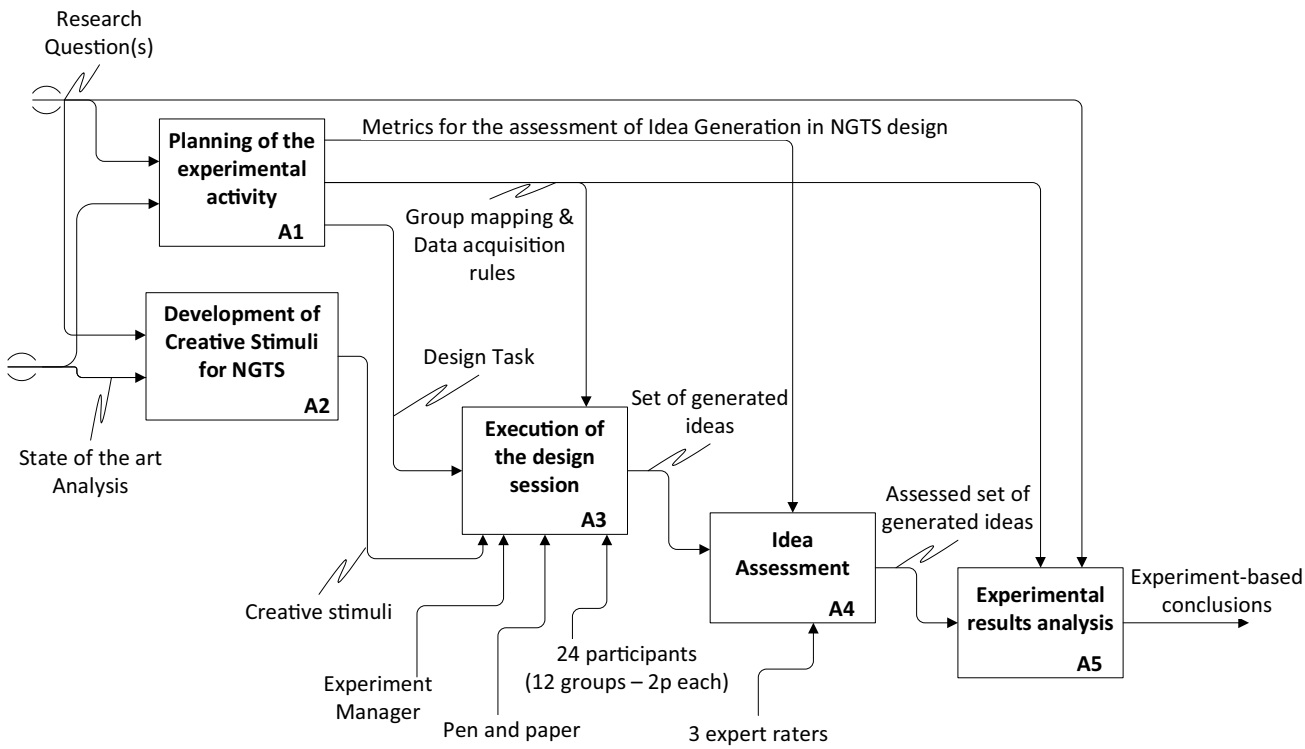



**Fig. 1** IDEF0 diagram of the research activity

context, with and without the support of creative stimuli. This means answering research questions as: "what is the average R&D engineers' performance to generate candidate ideas for NGTS?", "Do different stimuli produce different effects on R&D engineers' performance to generate candidate ideas for NGTS?" (these are inputs for activities A1 and A2).

Then, the authors propose an experiment to start gathering evidence about the above questions, as well as metrics to evaluate design outcomes, still with reference to the research objectives. As the literature does not directly address NGTS, relevant contributions were searched among those dealing with related concepts as characteristics of radical innovation, general criteria in assessing design and idea generation sessions (A1-Sect. 3 of the paper). As well, stimuli used to boost designers' creative performance in design sessions are explored as a means to improve idea generation (A2-Sect. 4). Those findings support the development of both the creative stimuli and the metrics for the experiment. After running the design session of the experiment according to the planning (A1 and A3-Sect. 5), the ideas generated along the experiment get assessed by a panel of 3 experts that rank them according to the metrics (A4). Such results, measured by counting the number of ideas satisfying specific threshold values for the tailored metrics, allow drawing preliminary conclusions on idea generation for NGTS with and without creative stimulation (A5-Sects. 6, 7).

## 3 Measuring candidate ideas for the next generation of technical systems

This section discusses NGTS with reference to relevant literature on innovation, to highlight their main characteristics. Then, it proposes tailored metrics, also with reference to creativity metrics, for the assessment of radical ideas suitable for developing NGTS.

Several terms in the literature can be referred to NGTS, despite this expression is never explicitly mentioned: radical innovation; radical technological change; technology paradigm shift; technology-push innovation; market-pull innovation; design-driven innovation; breakthrough innovation and radical novelty. E.g. in Cooper and Schendel (1976); Dosi (1982); Coombs et al. (1987); Anderson and Tushman (1990); Christensen and Rosenbloom (1995); Tripsas (1997); Geels (2004); Verganti (2008). The above-mentioned contributions classify radical innovation with respect to different factors as the magnitude, the drivers and triggers of innovation. The magnitude of innovation implies that an NGTS shows significant changes with respect to the previously existing system, instead of minor adjustments/improvements typical of incremental innovation (Trott 2008).

Market (Caves and Porter 1977; Porter 1979; Johne 1999) and technology (Pavitt and Wald 1971; Rosenberg 1976;

Mowery and Rosenberg 1979; Pavitt and Soete 1980; Soete 1981; Dosi 1982) are two main drivers of innovation, as scholars usually recognize and explain innovation from a technology-push or a market-pull perspective.

Interest in radical technological change originated with Schumpeter (1934). He was one of the first to claim that radical technological change is a powerful mechanism that can challenge the power of monopolists (i.e: replacing well-established solutions). Later on, the literature focused on product characteristics to explain drivers of innovation. Improvements of functionality (generally coming from technology-push innovation processes) and the customer-centred perception and interpretation of design (generally due to market-pull innovation processes) are two of them. Shifts in technological paradigms are often coupled with shifts in socio-cultural contexts (Geels 2004); therefore, it is not uncommon that a technological innovation implies that the users perceive the proposed solution with a new meaning. And such a meaning typically deals with the satisfaction of users' utilitarian needs, including affective and socio-cultural ones (Verganti 2008). Designers give meaning to products using a specific design language through a set of signs, symbols, and icons (style is just an example of this), which deliver the message (Pucillo et al. 2016). Table 1 summarizes the main characteristics of innovation (using a retrospective approach) with reference to the sources they come from.

The above list of features shows two main pieces of evidence. First, radical innovations can be identified with certainty only after observing a positive reception by the market. Second, novelty strongly connotes innovation. The former means that ideas and concepts are hard to classify as radically innovative because of their level of abstraction and vagueness, despite this could be beneficial for strategy plans in companies. The latter, in turn, shows that novelty belongs to several aspects. New user, new meaning, new language/interpretation, a new combination of principles and setting are descriptors of the changes the innovation brings, even if with reference to a specific context. Nevertheless, the evaluation of the design proposal for NGTS has to take into account the above characteristics, as radical innovations directly stem from radical ideas.

Different authors in design creativity literature have proposed criteria for idea evaluation, with reference to different purposes (Massetti 1996; Gero 1996; Wierenga and Bruggen 1998; Shah et al. 2003; Nijstad et al. 2002; Howard et al. 2006, 2008; Perttula and Sipilä 2007; Linsey et al. 2010; Runco and Jaeger 2012). Two main threads can be recognized for idea measurement: number/quantity of ideas (Nijstad et al. 2002; Shah et al. 2003; Perttula and Sipilä 2007) and quality of ideas (Wierenga and Bruggen 1998; Shah et al. 2003). The mixed approach of Shah et al. (2003) measures ideation effectiveness of design processes (NGTS design represents a specific one) according to four characteristics:

- quantity of ideas (number of ideas);
- variety of ideas (diversity of ideas, as a measure of the exploration of the design space);
- novelty of an idea (novelty with reference to existing technical system—ex-ante evaluation—or as the originality among the ideas—ex-post-evaluation);

**Table 1** Features of radical innovations as extracted from the mentioned references. To be used to characterize NGTS

| Main characteristics of radical innovation as the characteristics of the next generation of technical systems | Retrieved from |
|---|---|
| Completely new or significantly different in meaning or functionality | |
| Useful | Patent Law |
| Wider expectations for same market (New requirements of same users) | Schilling (2010) |
| Same or wider expectations for a new market (Same or new requirements for new users) | Schilling (2010) |
| New meaning or new language | Pucillo et al. (2016) and Verganti (2008) |
| Conquer the market dominantly | Verganti (2008) |
| New technology (in one of the scopes of hardware, software or orgware) | |
| Acceptable but not obvious to field experts | Patent Law |
| Acceptable level of novelty by the market | Shane (2001) and Dahlin and Behrens (2005) |
| Constitutes the core of the change | Silverberg (2002) |
| New combinations of selected principles derived from natural sciences and selected material—recombining already established elements | Fleming (2001) |
| Bringing in an established element into a new setting | Hargadon and Sutton (1997) and Van de Poel (2003) |
| Resolving contradictions | Bledow et al. (2009) and Altshuller (1988) |
| Less costs, harms and efforts/resources consumptions | Borgianni et al. (2012) and Becattini et al. (2015a, b) |

- quality of an idea (capability to address the objectives successfully).

With reference to quality metrics, some authors share the same vision and talk about "appropriateness", others focus on "unexpectedness" (un-obviousness) with respects to the target task (Massetti 1996; Gero 1996; Howard et al. 2006, 2008; Runco and Jaeger 2012; Becattini et al. 2015a, b). Linsey et al. (2010) consider quality as an index related to the technical feasibility of generated ideas.

As briefly mentioned above, the novelty of an idea can be seen from two angles. One is the technological perspective, which corresponds to the diversity from the state of the art. The other is the market-oriented one, which entails the new user's interpretation of the technical system, i.e. its meaning, which also deals with the capability of satisfying different/new needs. Within the scope of this paper, and in line with the design creativity literature, novelty is for assessing the diversity with reference to the state of the art in technology.

As existing metrics cannot capture the capability to breach new/different markets, this requires the introduction of a novel criterion. For the above considerations, the authors think that "relevance" (for a target audience) can be a good candidate to map the idea with respect to existing or potentially emerging markets.

These two criteria, however, are not sufficient to map design ideas and identify candidates for NGTS. Ideas should be also assessed in terms of their "time-to-market" and, if adopted, become innovations. To this purpose, the dimension of "quality", here meant as technical feasibility (Linsey et al. 2010), is a good candidate to grab the chances of the idea to be turned into a product ready to reach the market.

However, the intrinsic radical nature of candidates for NGTS allows for a more futuristic vision, while the current (hic et nunc) viewpoint on technical feasibility would be limiting. To this purpose, here the metrics to grab the capability to reach the market takes the name of "technical plausibility". In fact, R&D engineers (target audience of the creative stimuli) typically have the expertise to figure out reasonably feasible solutions that can sound futuristic for outsiders.

As technical experts should use the metrics to score ideas and identify a candidate for NGTS, a 4-level Likert scale differentiates scores for each criterion. Table 2 shows the 3 criteria above defined as metrics (novelty, relevance and technical plausibility) and the related scores (with their description). The metrics are also mapped to the characteristics of radical innovation already presented in Table 1.

Table 2 shows partial overlapping for the three metrics. Nevertheless, the repetition of some characteristics of radical innovation in more than one criterion is the unavoidable consequence of the nature of radical innovations, as technological leaps are usually tangled with societal changes (Geels 2004).

Experts will use these criteria to evaluate and rank ideas according to the levels described in Table 2. Candidate ideas for NGTS should be selected among those reaching or overcoming a threshold score (more than 2) for each of the three criteria. Candidates and ideas, in general, will be then measured in quantitative terms.

## 4 Tailoring creative stimuli for NGTS-design and R&D engineers

The literature on design stimuli can be studied according to very different perspectives. Contributions on stimuli take into account different contents/domains (e.g. biological/technological sources of inspiration); communication channels/modalities (e.g. textual/graphical) as well as the analogical distance between the source of inspiration and the target system to be designed. As this research aims at developing creative stimuli for NGTS, literature should be explored accordingly. The analysis of the state of the art shows that there exist no direct references about NGTS-oriented design stimuli. Nevertheless, there exist researches focusing on the proficient generation of novel ideas, e.g. on high-level generativity (Le Masson et al. 2016). As the effects of design stimuli have been typically studied in design cognition literature, it seems reasonable to investigate potential sources of creative stimulation consistently with the two main families of methods and tools there explored. On the one hand, the search should focus on methodological approaches e.g. design strategies, procedures… On the other hand, it should focus on precedents, e.g. examples, hints… The following subsections first briefly review and discuss precedents (Sect. 4.1) and strategies (Sect. 4.2) as generally representative of two different families of design stimuli, then it presents the rationale behind three different developed sets of creative stimuli for designing NGTS.

### 4.1 Design precedents

Precedents in design are defined as designer's prior knowledge and experiences. Moreover, precedents also include contents from any other source provided to designers as a means to allow them to access memory and foster thinking (Jones and Thornley 1963; Tulving 1991; Visser 1995; Eckert and Stacey 2000; Pasman 2003; Lawson 2004; Dix 2004). Precedents are typically proposed as stimuli/idea triggers that leverage different modalities of communication/channels of representation (e.g. graphical, textual, mixed…). Pasman (2003), Lawson (2004) and Eilouti (2009) explored prior solutions of the target technical system. Linsey et al. (2010) studied the effect of a collection of examples of other technical systems, distinguishing close or far domains with reference to the target technical system. Others focused on

**Table 2** Criteria and sub-criteria for assessing candidate ideas for the next generation of the technical systems (references as for Table 1)

| Criteria | Score/criterion | Mentioned characteristics in literature |
|---|---|---|
| Novelty | - Existing in the market/Already in use (score 1)<br>- Existing concept, not available on the market (score 2)<br>- Existing feature or trait in other fields of application, never applied to the domain of this product (score 3)<br>- Novel feature or trait (score 4) | Completely new or significantly different in meaning or functionality<br>- Useful<br>- Wider expectations for same market (New requirements of same users)<br>- Same or wider expectations for a new market (Same or new requirements for new users)<br>- New meaning or new language<br>- Conquer the market dominantly<br>New technology (in one of the scopes of hardware, software or orgware)<br>- Acceptable but not obvious to field experts<br>- Acceptable level of novelty by the market<br>- Constitutes the core of the change<br>- New combinations of selected principles derived from natural sciences and selected material<br>- Recombining already established elements<br>- Bringing in an established element into a new setting<br>- Resolving contradictions<br>- Using slack resources<br>- Less costs, harms and efforts |
| Technical plausibility | - Against laws of physics (score 1)<br>- Not against laws of physics, but sounds infeasible (score 2)<br>- Sounds infeasible with current knowledge but presumably achievable with further research in the field (score 3)<br>- Sounds feasible with current knowledge (score 4) | New technology (in one of the scopes of hardware, software or orgware)<br>- Constitutes the core of the change<br>- New combinations of selected principles derived from natural sciences and selected material<br>- Recombining already established elements<br>- Bringing in an established element into a new setting<br>- Acceptable but not obvious to field experts |
| Relevance | - Neither for the current usage of the system nor for potential interpretations for the future society (score 1)<br>- No benefits foreseen for the current usage of the system in the current society, but potential relevance in specific (narrow) niches of members of future society (score 2)<br>- No benefit for the current usage of the system in the current society but potential benefits (interpretation) perceived for different usage in a future society (score 3)<br>- Benefits also for the current society (score 4) | Completely new or significantly different in meaning or functionality<br>- Useful<br>- Wider expectations for same market (New requirements of same users)<br>- Same or wider expectations for a new market (Same or new requirements for new users)<br>- New meaning or new language<br>- Acceptable level of novelty by the market<br>- Conquer the market dominantly |

hints for considering requirements (Downing 2003), templates describing an entire class of solutions (Senbel et al. 2013) or hints about specific characteristics of prior solutions or other examples such as function and behaviour (Doboli and Umbarkar 2014). Such kind of studies usually measures the effects of stimulation directly on design proposals, e.g. the outcomes of the design session or process.

Precedents are provided into two main forms to designers during design sessions. One or an unstructured collection of prior solutions for the target technical system and relevant designs and examples of other technical systems are typically considered examples of singular precedents. On the other hand, they can come as a structured representation of previous knowledge and experiences. Heuristics, ways of designing, templates of an entire class of solutions, solution characteristics or hints are examples of structured precedents. In both these two forms, the inherent goal is the same: precedents should be capable of supporting an effective and efficient design thinking, so as to trigger a fluent idea generation processes.

Previous researches show that the effects of different precedents are mostly studied with respect to the quantity, novelty, variety of the design results; while fewer studies consider quality and utility. Table 3 summarizes the main findings of the reviewed studies.

Table 3 collects 34 different published studies. 6 out of 34 (20.6%) studies generally discuss the effects of precedents, while 21 (61.7%) and 7 (17.6%) focus the effects of singular and structural precedents respectively. The effects of precedents are also considered according to the main dimensions of creativity presented in Sect. 3, as these are crucial indexes describing the idea generation effectiveness of the

**Table 3** Previous studies about effects of different kind of stimuli on the design proposals

| Type of precedent | Dimension of creativity | Positive effect on specific dimensions of creativity | Negative effect on specific dimensions of creativity | Positive effect on creativity |
|---|---|---|---|---|
| Generic (not specified) | Novelty | Akin (2002), Eilouti (2009) and Gonçalves et al. (2013) | Chua et al. (2008) and Heylighen et al. (2007) | Ishibashi and Okada (2006) |
| | Quantity | | | |
| | Variety | | | |
| | Quality | | | |
| Singular precedents | Novelty | Chan et all (2011), Dunbar (1997), Fu et al. (2013), Linsey et al. (2010), McKoy et al. (2011), Moreno et al. (2014, 2015), Tseng et al. (2008) and Weisberg (2009) | Jansson and Smith (1991) and Smith et al. (1993) | Nijstad et al. (2002) |
| | Quantity | Simonton (2010) and Tseng et al. (2008) | Jansson and Smith (1991) and Purcell and Gero (1992) | |
| | Variety | Benami and Jin (2002), Crilly (2015), Kershaw et al. (2011), Mak and Shu (2008), Simonton (2010), Toh et al. (2013) and Youmans (2011) | Helms et al. (2009) | |
| | Quality | Dunbar (1997) and Weisberg (2009) | | |
| Structural precedents | Novelty | Goldschimdt (2011), Oxman (1990) and Zahner et al. (2010) | | Marslen-Wilson and Tyler (1980) |
| | Quantity | Liikkanen and Perttula (2006) | | |
| | Variety | Lane and Jensen (1993) and Luchins (1942) | | |
| | Quality | | | |

proposed idea triggers. The table clearly highlights that most of the evidence shows that precedents increase novelty, variety and in general creativity, though there are some studies that show contradictory results (i.e.: Chua and Iyengar 2008; Heylinghen et al. 2007; Jansson and Smith 1991; Purcell and Gero 1992; Helms et al. 2009). The table also shows that experimental outcomes are more controversial when designers deal with singular precedents and examples. Structural precedents (e.g. organized into abstract categories or paired to highlight similarities and dissimilarities), on the contrary, show a generally positive impact on the different dimensions of design creativity. A relatively recent contribution by Doboli and Umbarkar (2014), not included in Table 3, considers both structural and singular precedents and for both these stimuli they noticed no specific effects on novelty (except for the stimulation with set of new requirements for which the correlation is positive) or variety (except for a slight reduction of idea diversity with generic precedents). On the contrary, they recorded a general improvement of idea quality (and utility/usefulness) due to the exposition of creative stimuli.

The above results of the investigation highlight the need for carrying out further studies on the effectiveness of precedents (stimuli/trigger) for idea generation. This becomes extremely true especially with reference to the effects they trigger on experts or professionals, as just 5 out of the above-mentioned references explore the effect of stimuli on non-student subjects.

### 4.2 Design strategies

Strategies in design belong to the sphere of designers' behaviour. It includes the sequences of activities (problem formulation vs idea generation) and design moves (analysis, synthesis, evaluation) carried out in the design process, as well as the time dedicated to them. Understanding the design creative process will provide information that scholars can reuse to enhance designers' creative performance as well as the quality of the solution to be designed (Howard et al. 2008).

Design cognition studies designers' thinking patterns and highlighted at least three main areas of interest: the strategy as a whole, problem formulation, solution generation (Cross 2001). Yet, just a few of them investigated the effects of the strategies on quantity, novelty, quality or variety of design proposals. Cross' (2001) highlighted seven strategies

typically used in design, as witnessed in the referenced literature contributions:

1. Considering design problems as ill-defined problems (Akin 1978; Thomas and Carroll 1979) that can perhaps never be converted to well-defined problems, so proceeding to find a satisfactory solution rather than an optimum (Cross 2001);
2. Co-evolving the problem and solution until reaching a matching problem–solution pair through iterative cycles (Conradi 1999); undertaken through exploring partial structure of design space and solution space, generating some initial ideas in the form of a design concept (Cross and Dorst 1998), and bridging these two partial models through the articulation of the concept which enables the models to be mapped onto each other (Cross 1997);
3. Starting design using previous solutions as starting points to create designs with new goals, extra functions, and substructures inspired by previous designs (Pugh and Clausing 1996; Howard et al. 2008);
4. Rapid alternation of activities, which they measured as transitions between design actions and moves (Atman et al. 1999);
5. Framing a problematic design situation by setting the boundaries, selecting particular things for attention, and imposing on the situation a coherence that guides subsequent moves (Schön 1988). Only some constraints are given in a design problem; other constraints are introduced by the designer from domain knowledge and/or are derived by the designer during the exploration of particular solution concepts (Ullman et al. 1990);
6. Framing five times sequentially while it is done dominantly at the beginning of the design task and reoccurs periodically throughout the task (Goel and Pirolli's 1992); it is seldom done in one burst at the beginning of a design process (Schön 1988);
7. Scrapping initial design ideas and starting afresh with new design concepts and a suitable amount of alternatives (Smith and Tjandra 1998); a dominant influence is seen by initial design ideas on subsequent co-evolving problem and solution, even when severe problems are encountered and despite changes in the framing of the design situation (Rowe 1987; Ullman et al. 1990).

The above findings have to be taken into account when developing new design stimuli as strategies or procedures. However, it is also necessary to consider that R&D engineers, as representative of design professionals, tend to use their hierarchically structured plan in a rather ad-hoc, unsystematic and opportunistic way (Visser 1990). In fact, designers who follow a flexible-methodical procedure tend to produce good solutions. These designers work efficiently and follow a logical procedure. In comparison, designers with too-rigid adherence to a methodical procedure, or adopting very un-systematic approaches, produce mediocre or poor design solutions (Fricke 1993, 1996). Literature also shows that more efficient processes have positive correlations with both the quantity and quality of design outputs (Radcliffe and Lee 1989).

In general, one of the main differences between engineering design models and creative processes in psychology stands in divergent-convergent models (Howard et al. 2008). Divergent–convergent models differ from the traditional linear style by assuming some form of integrated evaluation and selection of ideas and concepts. This is potentially a useful outlook on design from a creativity perspective, as separating the generation and evaluation periods is considered a good practice for both lateral thinking and brainstorming (Osborn 1953).

### 4.3 Development of the creative stimuli

With reference to the above findings, three different set of stimuli are developed for the experiment described in this paper: two are based on design precedents (respectively singular and structural, see Sect. 4.1) and the third one focuses on a design strategy proposed as a technological procedure for inventive design.

#### 4.3.1 Pictorial representation of trends of evolutions of technical systems

As for Table 3, precedents generally increase quantity and novelty and diversity/variety (as they reduce fixation). Examples, especially non-textual ones, are the most common. For example, Sarkar and Chakrabarti (2008) studied the effects of different modalities of stimuli administration on design outcomes. Moreover, the positive effects of structural precedents appear to be less controversial than singular precedents.

This suggests that it can be convenient to develop one set of structured precedents to stimulate creativity as a pictorial representation of examples. This is to enable a quick and visual interaction with the example, without the need of information processing through language, which is assumed to have a stronger impact on the consumption of cognitive resources.

Templates describing an entire class of solutions are one kind of structural representation of precedents, which enable for the further composition of examples. Among them, trends of evolution of the technical system describe, each, an entire class of solutions of technical systems, generation after generation consistently with the trend recognized in technology. Trends and patterns of evolution are one of the most powerful TRIZ tools, in that they display system's evolution potentiality and speed up the

generation of new solutions for technical problems (Domb 1999; Sawaguchi 2001; Zlotin and Zusman 2001). The structure of such kind of stimuli is based on an evolution tree that represents the evolutionary path describing previous generations of the technical system as well as possible developments (Shpakovsky 2006).

Technical trends of evolution, moreover, leverage knowledge that is familiar to R&D engineers, as the content of the stimuli deals with examples that are familiar to professionals with a background in science and technology.

These stimuli are proposed as five evolution trees, including one technical system each. The authors decided to develop five examples as literature does not report any evidence about the effectiveness of higher or lower number of examples to be proposed as stimuli. Appendix 1 shows the picture of the evolution tree of the five selected systems.

#### 4.3.2 Abstract of patents related to the function of the target system

Within the stimuli considered in Table 3 for singular precedents, there are previous solutions and novel artworks typically presented as examples. This form of precedents is effective in increasing novelty and diversity if they are presented with more diversity and ambiguity (despite the mentioned controversial results).

Patents are a type of representation of novel artworks and at the same time are part of the state of the art, as they deal with existing inventions. A patent is a set of exclusive rights granted by a sovereign state to an inventor or assignee for a limited period of time, in exchange for detailed public disclosure of an invention. An invention is a solution to a specific technical problem. A patent may include many claims that define specific property rights. These claims must meet relevant patentability requirements, such as novelty, usefulness, and non-obviousness.

Both patents about previous solutions of the target system and examples of different technical systems can be considered as possible options for creative stimulations, where the former represent near-field analogies and the latter more distant ones.

Patents, in principle, have also the advantage to be written and compiled with technical and formal language that should be understandable by readers “skilled in the art” as R&D engineers are supposed to be.

To prepare these stimuli, the summary of 5 patents related to the behaviour of target system was selected, since literature refers that this kind of precedents is also effective in increasing novelty (see Table 3, e.g. Oxman 1990; Goldschmidt 2011). As for the previous set of stimuli, 5 patents have been chosen for consistency. The characteristics of the selected patents are described in Appendix 2.

#### 4.3.3 An engineering procedure for designing the next generation of technical systems

Section 4.2 presented seven strategies that designers appeared to follow with higher chances of success in design and their various nature is consistent with the ad-hoc and opportunistic behaviour of designers mentioned in the above-referenced studies. Nevertheless, it is almost impossible to stimulate designers with an ad-hoc strategy that is tailored to the specific design task. This would make it not representative of a general design situation. To overcome this limitation, the structured strategy should leverage common phases in design processes of idea emergence and problem framing. For instance, the redefinition of the new task goals and constraints, the identification of requirements and system boundaries. All these design activities to be carried out in cycles of analysis–synthesis–evaluation (Akin 1978; Mc Neill et al. 1998; Gero and Kannengiesser 2004). From this perspective, TRIZ-based anticipatory design approaches (Kucharavy and De Guio 2008; Cascini et al. 2009, 2011) leverage specific design models, organized as structured sequences of steps to support the above-mentioned design activities with a future-oriented goal, as it should be for NGTS. The procedure developed to stimulate R&D designers’ strategy elaborates on these approaches by integrating models in a step-based procedure. It proceeds by searching current problems and solved problems to propose the NGTS, according to the assumption that behind a problem there is a technical issue or a user’s need that sooner or later needs to be solved or made irrelevant (Kucharavy and De Guio 2005).

Problems, as well as non-fully satisfactory situations, should be extremely familiar to R&D engineers, as they work daily to fix them and improve existing solutions.

Within the scope of the development of this stimulus, consistency with precedents cannot be kept because of the different nature of the stimulus. This said, the proposed procedure is composed of 5 steps that, on purpose, should require an expert in the field to work for 30 min to complete it. Appendix 3 details the steps of the developed procedure.

The above set of stimuli was selected to inspire different groups of designers. This allows comparing the ideas they generated during the experiment using different stimuli, as described in the next section.

### 4.4 Description of the experiment and rules for data analysis

This exploratory study observes R&D engineers’ performance with and without the use of creative stimuli in designing NGTS.

For what concerns the experiment dynamics, it consisted of two main design sessions: the first session carried out without any creative stimulation and the second one

with the 3 sets of stimuli, as presented in Sect. 4.3. Each session lasted 45 min with a break of 10 min in between. This duration of the design session is consistent with the evidence that brainstorming-based design session's productivity decreases after half an hour, while the best ideas are generated during first 15 min (Howard et al. 2010).

The design task was briefly presented to R&D engineers during the few minutes that precede the first session and did not change between the sessions. To avoid cross-effect of different stimuli on the teams, teams were randomly divided into four groups and received one different set of stimuli each for the second round. One of the groups received no stimuli in the second round and played the role of the control group. Figure 2 shows the setting of the experiment.

During the first round, the participants were free to design, according to their normal behaviour and it is expected that most teams proceeded through brainstorming. Evidence from the literature witnesses that traditional brainstorming is still the preferred technique in industry for producing innovation in teams (Howard et al. 2010), despite the growing body of research identifying its limitations (Isaksen and Gaulin 2005). Since the beginning of round 2, the creative stimuli of Sect. 4.3 were provided to teams for each of the three groups receiving the treatment (the group receiving the procedure had limited freedom due to the sequence of steps of the stimulus). Except for the treatment, the same rules as round 1 apply. This kind of setting (1st round: no treatment; 2nd round: treatment + control group) allows checking the effectiveness of stimuli in a more demanding condition. The first round is meant to exhaust designers' generativity, making harder to find new concepts during the second round of design. This also allows for paired comparisons before and after the treatment with the same group.

24 Iranian R&D engineers participated in the experiment as members of 12 teams (2 people each). They were enrolled as subjects for the experiment after a call for volunteering engineers. The call requested for subjects having at least 3 years of experience in R&D departments of industrial companies working on new product development processes. The subjects were selected independently from the market domain of the company they work for. Volunteers from different companies were organized in teams of two engineers. The criterion to build up teams focused on randomization and optimization of time and human resources for the experiment execution. The profile of volunteering subjects can be summarized as follows:

- Gender: 75% male and 25% female (18 Men and 6 women);
- Ages: ranged from 28 to 40 years;
- Level of education: 12% PhD, 71% master and 17% bachelor;
- Engineering field: 37% industrial engineering, 21% mechanical engineering, 13% computer engineering, 13% electrical engineering, 8% design, 4% polymeric material engineering and 4% textile engineering;
- Experience in R&D units of Iranian companies: 67% (between 7 and 9 years), 16% (between 5 and 6 years) and 17% (between 3 and 4 years);

The whole experiment for 12 teams was scheduled and performed in series during 1 week in the summer of 2014. Each day, 2 teams worked separately, one in a morning design session and the second in the afternoon design session. This prevented members of different teams to share

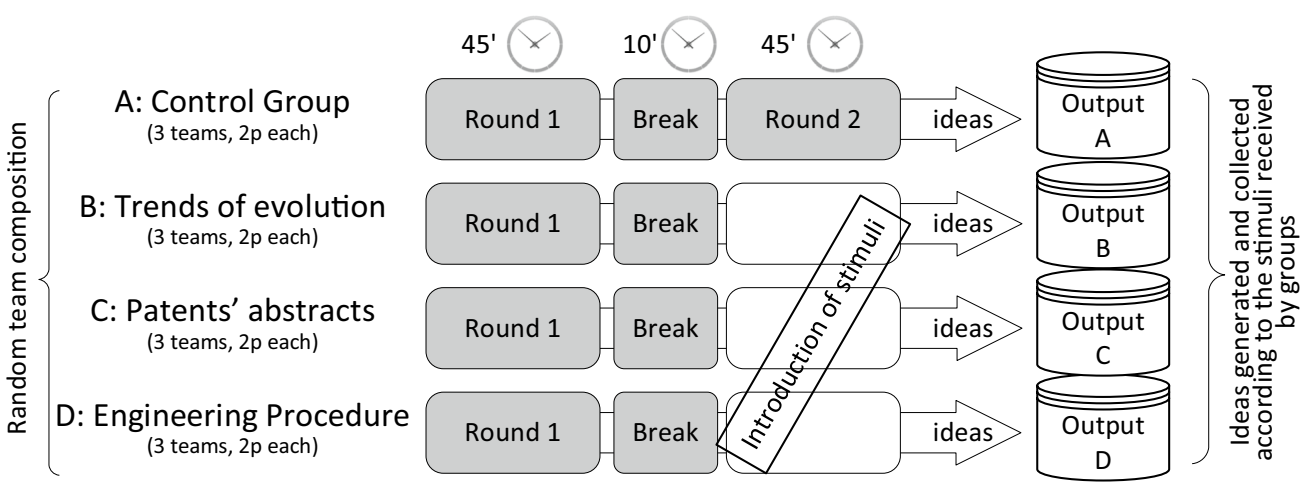



**Fig. 2** Experiment setting

ideas with teams or simply individuals participating in the experiment. Participants coming from the same company and involved in different design sessions were told to discuss the design task just with colleagues that have already participated in.

Each of the 12 teams had at least one R&D engineer from the Industrial or Mechanical domain.

For what concerns the design task, the design teams were asked to generate ideas for the next generation of a domestic refrigerator. This product is a technical system everyone uses in everyday life and it holds several devices that span the most various fields of technology, so that all the participants can provide ideas from different angles. This is also done to ease leveraging prior knowledge and experience to generate and develop design ideas. All the participants were also familiar with the mechanism of cooling in a fridge, as it is part of the high school syllabus for the Iranian education system. The task was also open-ended as specific requirements were not provided. Such freedom was given in order to observe the natural behaviour of participants while they generated ideas and elaborate on them.

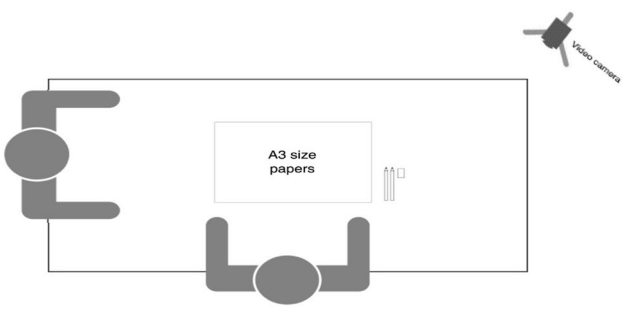



**Fig. 3** Experimental setting

The participants were asked to verbally interact to make it possible to record the speech and analyse the talk-aloud protocol to identify generated ideas for further assessment. The experiment was conducted in teams of two R&D engineers in a closed room, equipped with a video recording device to record the participants' voices. They were also equipped with markers, pen and A3 paper to draw and make annotations. Figure 3 shows the setting of the experimental room.

The participants were free to use the paper as a supportive tool, but they were also asked to explain their writings and drawings, as the analysis would be limited to the verbal interactions. Teams used pen and paper in various ways. Figure 4 shows two examples: one which is rich in text and poor of drawing and vice versa.

Three experts received the list with the whole set of generated ideas as emerged from the transcripts. They ranked each idea according to the metrics presented in Sect. 3. Candidate ideas for the NGTS required scores 3 or 4 by all three experts, for each of the three criteria. Ideas taking scores 3 or 4 for just one or two out the 3 metrics are considered for the evaluation of the effect of stimuli over the different categories separately. Ideas got counted once per group even if they are repeated (just first occurrences counted). Ideas are to be compared quantitatively so that it allows for comparisons between different treatments.

The general characteristics of the experts involved in the evaluation can be summarized as below:

- Gender: male;
- Ages: ranged from 30 to 50 years;
- Level of education: PhD;
- Engineering field: mechanical engineering;

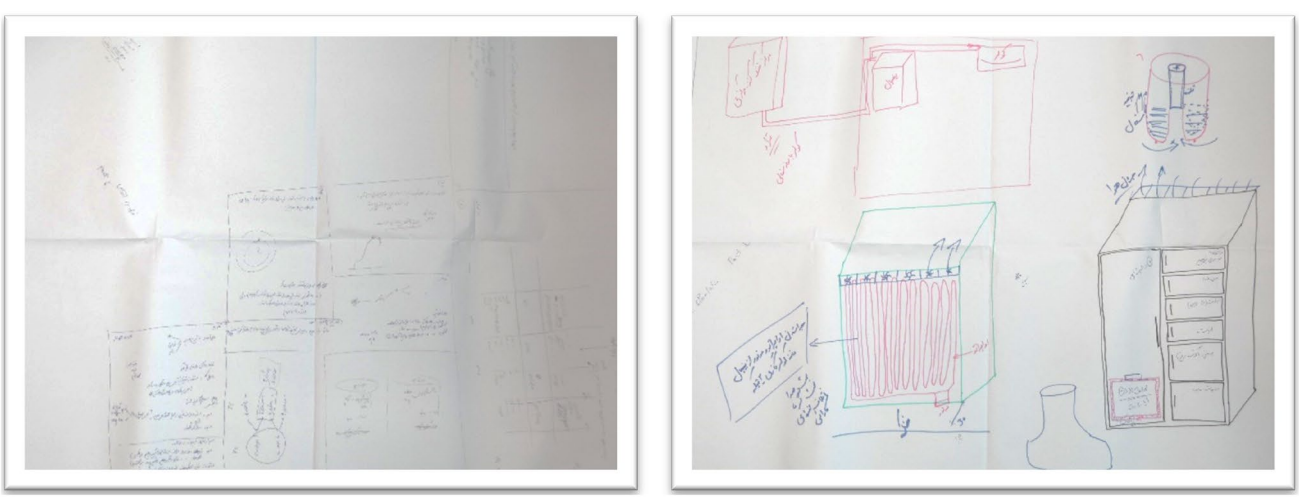


**Fig. 4** Two examples of notes and drawings gathered after the experiment

- Experiences: More than 10 years experience in problems solving and technology forecasting. Solid and updated knowledge on technologies for domestic appliances.

## 5 Correlations between R&D engineers' performance and creative stimuli for NGTS

This section presents the results obtained during the experiment with reference to the research questions proposed in Sect. 2. The following subsections discuss the outcomes of ideation with and without the influence of creative stimuli.

### 5.1 Duration of design sessions and effects of creative stimuli

Despite the duration of 45 min proposed to the participants, each team dedicated a different amount of time to complete the task (1st session: 32′–50′; 2nd: 25′–55′). Figure 5 shows that just 2 teams (16.8%) asked for more time, suggesting that the duration of the session, with or without stimuli, is correctly limited.

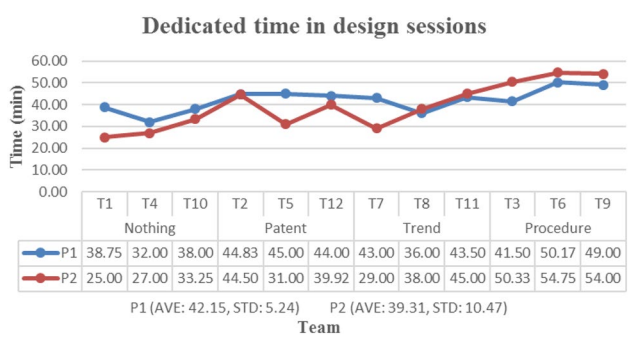



**Fig. 5** Comparison of dedicated time for performing the task in the first and second design sessions in respect to the kind of stimuli

In addition, round 2 shows decreased durations (avg −14.5%) except for the teams treated with the engineering procedure (+13.09%). Considering the tendency of teams in the group with no treatment to spend less time in the second session, it can be supposed that the teams with the engineering procedure needed more time than what requested for applying the other precedent-based stimuli (patent, trends).

### 5.2 Number of generated ideas (productivity) and effect of creative stimuli

The number of generated ideas is used to study productivity for uniform durations of design sessions. On the contrary, the rate of idea generation with respects to the actual duration of design sessions allows for more consistent comparisons in case of sessions that concluded after a variable amount of time. Figure 6 shows the number of ideas (left) and the rate (right) of idea generation per team.

During the two design sessions, the teams generated 462 ideas (1st: 307, 2nd: 155), showing that round 2 was half productive. The average number of generated ideas for each team is 26 (SE = 7) for the first and 13 (SE = 9) ideas for the second session. The rate of idea generation decreases for almost all teams in the second session (avg: 0.31, SE = 0.26) compared to the first session (avg: 0.62, SE = 0.20), witnessing the partial exhaustion after the first round.

With reference to stimuli, the number of generated ideas decreases for all teams in all groups. The same is for the rate of idea generation. As they show the lower reduction, the groups that received trends and patents generally obtained better results.

### 5.3 Candidate ideas for NGTS

Candidate ideas have scores 3 or 4 on all three criteria of novelty, technical plausibility, and relevance by all 3 experts and just 16 (3.46%) out of 462 satisfy such condition. Considering the unique ideas without counting repetitions across

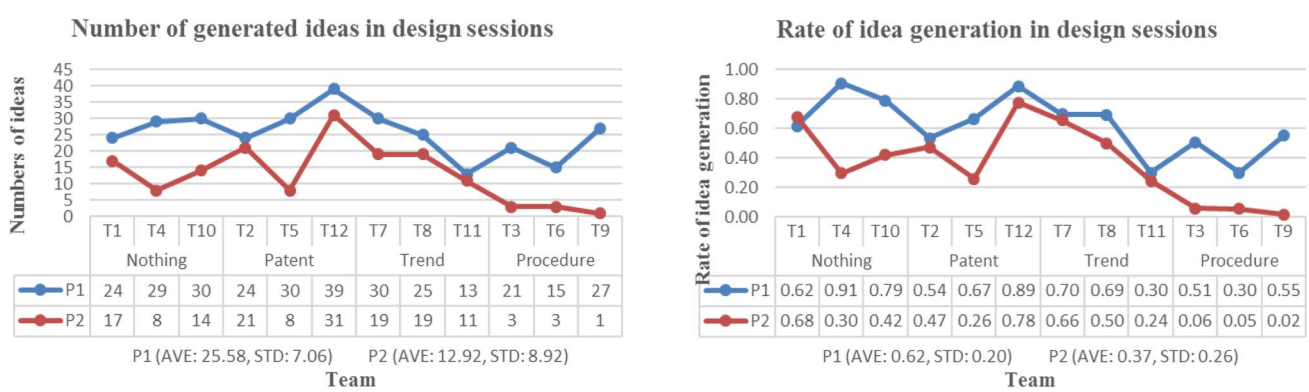



**Fig. 6** Comparison of team productivity in the first and second design sessions with respects to the kind of stimuli

**Table 4** Appearance of candidate ideas in design sessions

| No. | Idea | Team | Time (min) |
|---|---|---|---|
| 1 | Changing the mechanism of cooling by finding an organic element that absorbs heat for its metabolism | 4 | 4.25 |
| | | 6 | 7.67 |
| | | 5 | 15.17 |
| | | 12 | 20.75 |
| 2 | The size of fridge changes according to new place when we move our house | 12 | 21.17 |
| | | 5 | 32.75 |
| | | 9 | 45.25 |
| | | 10 | 79.5 |
| | | 10 | 81.17 |
| | | 8 | 15.25 |
| 3 | The fridge shows the characteristics of food such as ingredients, calories, its healthiness… | 10 | 26.25 |
| | | 12 | 60.17 |
| 4 | Fridge that listens to users' talks and act as a friend | 2 | 17.83 |
| | | 7 | 77.17 |
| 5 | Fridge that accepts orders and gives users the fruit or vegetables in the right time according to the ripeness | 2 | 21.83 |
| 6 | Using the heat of condenser to melt ice to have purified and drinking water instead of using filters | 5 | 44.5 |

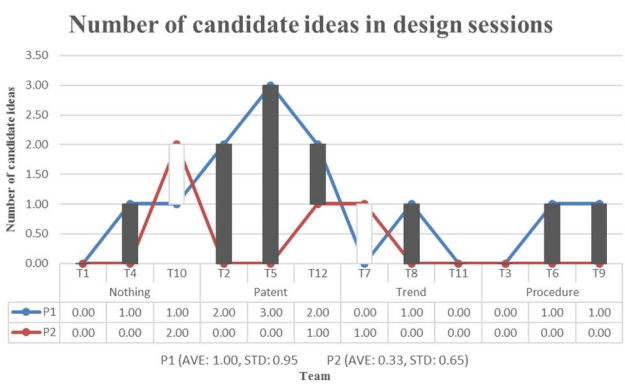



**Fig. 7** 1st vs 2nd round comparison of team productivity

teams (overall they are 123), just 6 of them are unique (approx. 5%). Table 4 collects candidate ideas for NGTS.

Only 4 ideas (25%) emerged in the second session and different teams already generated them during the first session (candidate ideas for NGTS emerged at least once without any treatment). Figure 7 shows candidate ideas for NGTS by the teams and by round of emergence.

Three teams generated 3 candidates and three generated none. Light and dark bars, respectively, highlight raises and drops of productivity for candidate ideas for NGTS as differences. Two light bars out of 12 (approx. 16.6%, 1 of these two occurrences is in the control group) show that none of the treatments is effective in this context.

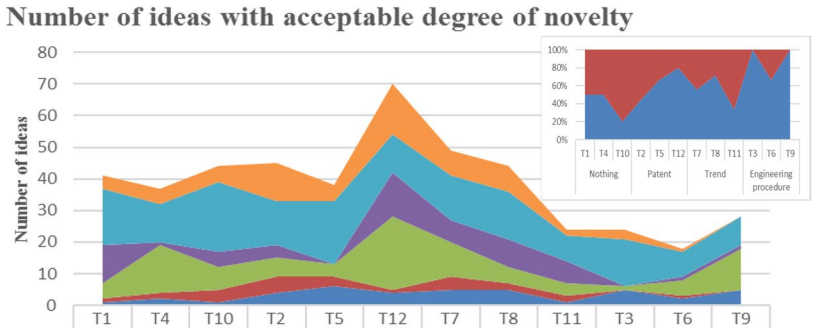
To confirm the consistency of experts' opinions and the reliability of the criteria for assessment, the authors decided to double check the goodness of the evaluation with a second round of idea assessment. As three new equivalent experts (for expertise) were not available, the new panel consists of 9 experts. They were asked to evaluate a subset of 12 ideas, including the 6 candidate ideas as they emerged from the results of the first round of evaluation.

The general characteristics of the 9 experts involved in the second round of idea evaluation can be summarized as below:

- Gender: 90% M–10% F;
- Ages: ranged from 30 to 49 years;
- Level of education: 34% PhD and 66% Master;
- Engineering field: 68% mechanical engineering and 32% Other fields;
- Experiences: More than 10 years experience in problems solving and technology forecasting.
- Culture: 50% European and 50% Iranian;

The Interclass Correlation Coefficients (ICC) were studied for the results of the 9 experts' assessment on each of the 3 desired criteria separately. The results show 0.722 consistency (good) for Novelty, 0.905 consistency (excellent) for technical plausibility, and 0.594 consistency (fair) for relevance. The largest discrepancies for relevance might also depend on the 2 different cultures of the involved subjects. The results of this new round of evaluation confirm that the 6 accepted ideas are to be considered as candidate ideas for NGTS.

As the metrics have three criteria, the following subsections explore idea generation with and without the support of stimuli considering one criterion at a time.




| Team | T1 | T4 | T10 | T2 | T5 | T12 | T7 | T8 | T11 | T3 | T6 | T9 | Sum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nothing | | | Patent | | | Trend | | | Engineering procedure | | | |
| Others .P2 | 4 | 5 | 5 | 12 | 5 | 16 | 8 | 8 | 2 | 3 | 1 | 0 | 69 |
| Others .P1 | 18 | 12 | 22 | 14 | 20 | 12 | 14 | 15 | 8 | 15 | 8 | 9 | 167 |
| Accepted by majority .P2 | 12 | 1 | 5 | 4 | 0 | 14 | 7 | 9 | 7 | 0 | 1 | 1 | 61 |
| Accepted by majority .P1 | 5 | 15 | 7 | 6 | 4 | 23 | 11 | 5 | 4 | 1 | 5 | 13 | 99 |
| Accepted by all .P2 | 1 | 2 | 4 | 5 | 3 | 1 | 4 | 2 | 2 | 0 | 1 | 0 | 25 |
| Accepted by all .P1 | 1 | 2 | 1 | 4 | 6 | 4 | 5 | 5 | 1 | 5 | 2 | 5 | 41 |
| Sum | 41 | 37 | 44 | 45 | 38 | 70 | 49 | 44 | 24 | 24 | 18 | 28 | 462 |

**Fig. 8** Level of novelty of generated ideas in first and second design sessions

## 5.4 Candidate ideas (NGTS) for what concerns novelty

Figure 8 shows the number of ideas with an acceptable level of novelty by all (3) or majority (2 out of 3) of experts.

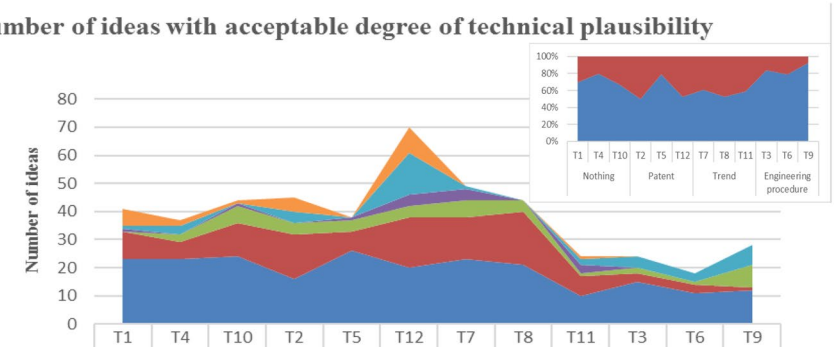
66 ideas (14.29%) got scored 3 and 4 by all the experts and 160 ideas (34.63%) by the majority of them (at least 2 experts); 236 ideas (51.08%) received lower scores. Whatever the stimulus and independently from its adoption, the majority of ideas got insufficient scores to be considered candidates.

The red colour surface shows that the most effective stimuli for generating novel ideas are patents and trends. With reference to both the red and the purple surface, this behaviour is more marked, especially with reference to trends.

## 5.5 Candidate ideas (NGTS) for what concerns technical plausibility

Figure 9 shows the number of ideas with an acceptable level of technical plausibility by all (3) or majority (2 out of 3) of experts.

For what concerns technical plausibility, the whole panel agreed that 341 ideas (73.81%) are technically plausible with score of 3 or 4. Figure 9 shows that, independently from stimuli, the largest majority of ideas got scored as technically plausible.




| Team | T1 | T4 | T10 | T2 | T5 | T12 | T7 | T8 | T11 | T3 | T6 | T9 | Sum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nothing | | | Patent | | | Trend | | | Engineering procedure | | | |
| Others .P2 | 6 | 2 | 1 | 5 | 0 | 9 | 0 | 0 | 1 | 0 | 0 | 0 | 24 |
| Others .P1 | 1 | 3 | 0 | 4 | 0 | 15 | 1 | 0 | 2 | 4 | 3 | 7 | 40 |
| Accepted by majority .P2 | 1 | 0 | 1 | 0 | 1 | 4 | 4 | 0 | 3 | 0 | 0 | 0 | 14 |
| Accepted by majority .P1 | 0 | 3 | 6 | 4 | 4 | 4 | 6 | 4 | 1 | 2 | 1 | 8 | 43 |
| Accepted by all .P2 | 10 | 6 | 12 | 16 | 7 | 18 | 15 | 19 | 7 | 3 | 3 | 1 | 117 |
| Accepted by all .P1 | 23 | 23 | 24 | 16 | 26 | 20 | 23 | 21 | 10 | 15 | 11 | 12 | 224 |
| Sum | 41 | 37 | 44 | 45 | 38 | 70 | 49 | 44 | 24 | 24 | 18 | 28 | 462 |

**Fig. 9** Level of technical plausibility of generated ideas in first and second design sessions

Teams receiving trends and patents show better results, suggesting that precedents are more effective than design strategies.

### 5.6 Candidate ideas (NGTS) for what concerns relevance

Figure 10 shows the number of ideas with an acceptable level of relevance by all (3) or majority (2 out of 3) of experts.

Relevant ideas scoring 3 or 4 (for a target audience) achieve the agreement of all the expert 326 times (70.56%). Also in this case, independently from the adoption of creative stimuli, the large majority of ideas have been rated as relevant and thus potentially addressing a market.

Both red and purple areas show that patents and trends (precedents) are more effective than design strategies to improve idea generation in this context.

## 6 Discussion

As there are no previous studies about the performance of R&D engineers dealing with an NGTS-design task, the results shown in Sect. 6 will be discussed just with reference to previous studies about the effect of stimuli during idea generation.

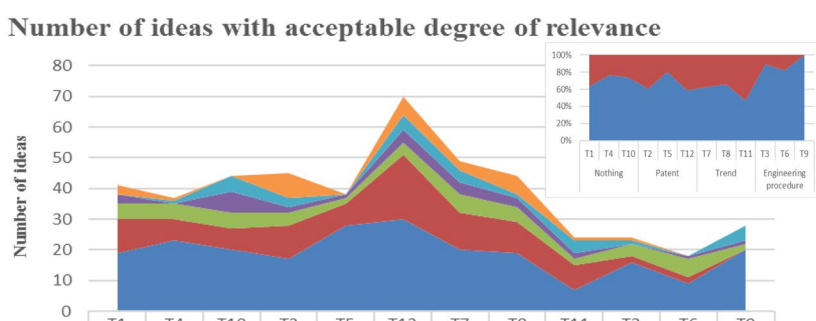
Pictorial representation of trends of evolution of technical systems (i), abstract of patents related to the function of the target system (ii) and an engineering procedure (iii) for designing the NGTS are the three types of stimuli developed and studied in the scope of this research.

In this research, the effectiveness of the proposed stimuli is studied in 12 design sessions, each of them organized into two rounds (just round 2 is with creative stimuli) for proposing the next generation of refrigerator, selected as the target technical system for the design task.

Consistently with the experiment dynamics, the first part of the experiment effectively exhausted the teams' generativity, as none of the teams generated a higher number of ideas in round 2.

To gather evidence about the effectiveness of stimuli, the changes in teams' performance for each group during the second session are considered and compared to the outcomes of the first round of the experiment. Table 5 ranks the effectiveness of stimuli with reference to the metrics adopted for this study.

The results of the experiment show that, independently from the stimulus, precedents (singular, as a patent, or structural, as evolutionary trends) are effective in triggering ideas that are relevant and technologically plausible. The results also show that trends and patents produce a positive effect in increasing the number of ideas with respect to the control group in the second session. This observation confirms the findings in Tseng et al. (2008), Nijstad et al. (2002) and Likkanen and Pertula (2006). The effect of trends and patents on the novelty of design proposals is not positive compared to control group, while the majority of previous researches show that examples and previous solutions increase novelty; e.g. Gonçalves et al. (2013), Goldschmidt (2011). Trends and patents are not effective in increasing novelty in the scope of this research, but this can also depend on the higher acceptable degree of novelty this research aims at capturing, with reference to NGTS. A biased judgement among experts




| Team | T1 | T4 | T10 | T2 | T5 | T12 | T7 | T8 | T11 | T3 | T6 | T9 | Sum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nothing | | | Patent | | | Trend | | | Engineering procedure | | | |
| Others .P2 | 3 | 1 | 0 | 8 | 0 | 6 | 3 | 6 | 1 | 1 | 0 | 0 | 228 |
| Others .P1 | 0 | 1 | 5 | 3 | 0 | 5 | 4 | 1 | 4 | 1 | 0 | 5 | 98 |
| Accepted by majority .P2 | 3 | 0 | 7 | 2 | 1 | 4 | 4 | 3 | 2 | 0 | 1 | 1 | 50 |
| Accepted by majority .P1 | 5 | 5 | 5 | 4 | 2 | 4 | 6 | 5 | 2 | 4 | 6 | 2 | 28 |
| Accepted by all .P2 | 11 | 7 | 7 | 11 | 7 | 21 | 12 | 10 | 8 | 2 | 2 | 0 | 29 |
| Accepted by all .P1 | 19 | 23 | 20 | 17 | 28 | 30 | 20 | 19 | 7 | 16 | 9 | 20 | 29 |
| Sum | 41 | 37 | 44 | 45 | 38 | 70 | 49 | 44 | 24 | 24 | 18 | 28 | 462 |

**Fig. 10** Level of relevance of generated ideas in first and second design sessions

**Table 5** The influence of different stimuli in order in the second session

| No. | Performance characteristics | Ranking of stimuli with respect to their effectiveness | | | |
|---|---|---|---|---|---|
| | | First | Second | Third | Fourth |
| 1 | Quantity of ideas | Trend | Patent | Control group | Procedure |
| 2 | Quantity of candidate ideas | Trend/ Control group | | Patent | Procedure |
| 3 | Quantity of ideas with acceptable level of novelty | Control group | Trend | Patent | Procedure |
| 4 | Quantity of ideas with acceptable level of technical plausibility | Trend | Patent | Control group | Procedure |
| 5 | Quantity of ideas with acceptable level of relevance | Trend | Patent | Control group | Procedure |

can also have affected this result, as novelty assessment is strongly influenced by the previous specific knowledge they have on subassemblies of the target system in an a priori evaluation. However, trends generally trigger a more positive impact than other stimuli as this better mitigates the drop of generativity.

A more comprehensive analysis of the results, which also considers ideas that were accepted by the majority of evaluators according to the three criteria with scores 3 and 4, shows that trends (which are a specific kind of structured precedent) reduce the drop of generativity with better results than all the alternative treatments of the experiment.

Despite the above results appear to be confirming the studies of Heylingen et al. (2007) and Chua and Iyengar (2008), the overall positive effect that precedents have on novelty is also measured within this experiment. Considering that the second round is less productive by design, the ratio of accepted ideas (score 3 or 4 by 3 experts) over the rejected ideas (score 1 or 2) allows checking their effectiveness after exhaustion. From this perspective, patents and trends slightly improve the results comparing the same team's performance of first and second round of a percentage around 5%.

Creative stimulation by means of a structured design strategy (the engineering procedure summarized in Appendix 3) demonstrated to be dramatically decreasing the fluency of idea generation in this kind of activities. On the contrary, it demonstrated a perfect efficiency in producing technically plausible ideas, as it is expected from a structured procedure.

The composition of design teams, as mentioned in Sect. 5, followed a randomization process, so that teams could be composed heterogeneously. This makes hard or just speculative any even preliminary conclusion on the effects of stimuli on R&D engineers having different expertise and background. To this regard, the experimental setting described above allows for the replication of the experiment with different controlled conditions (e.g.: homogenous expertise vs different stimuli).

## 7 Conclusion

This paper aims at clarifying the performance of R&D designers involved in the ideation of the next generation of technical systems (NGTS), as literature shows several pieces of evidence of methods and tools that more or less explicitly deal with design for radical innovation, high novelty, etc. The paper clarifies what should be meant as candidate ideas for NGTS and provides metrics to assess them, as literature generically refers to novelty, while radical ideas with innovation potential should be considered from different angles. From a broader perspective, it aims at studying the effects of some alternatives among the most effective categories of creative stimuli on their performance. This is to refine creative stimuli before they will be embedded into a serious game that should facilitate R&D engineers to face design tasks for NGTS with higher engagement and motivation. An experiment involving 24 Iranian engineers working on a design task (design the next generation of domestic refrigerators) allowed for testing their performance in terms of idea generation. The quantity of ideas, with reference to novelty, relevance for a target audience and technical plausibility are considered here as the main dimensions to identify a candidate for the next generation of technical systems (the above-mentioned metrics). Three experts rated ideas and a panel of nine confirmed their initial selection of candidate ideas for the next generation of the technical system, so that the results provide new evidence with a twofold objective. On the one hand, this evaluation helps shedd light on the ideation performances with and without creative stimuli. On the other hand, it confirms the applicability of the metrics to evaluate ideas for NGTS.

The results show that free ideation (brainstorming-like) allows for a good rate of productivity, as more than 1 idea emerge every 2 min (0.62 ideas/minutes, 0.2 SE) among teams. Moreover, on average, the teams generated 1 candidate idea each (SE 0.95). The 12 candidate ideas for NGTS are just 6 unique ideas (some of them are repeated) and they are just 3.9% of the total ideas generated in the first session. It is important to notice that a candidate idea for

the next generation of technical systems should satisfy the three criteria of novelty, technical plausibility and relevance by the whole panel of evaluators with high scores, which significantly reduced their overall amount. However, this is consistent with the nature of candidate ideas, as just a few concepts survived the whole development process and just a few of the solutions entering the market becomes actual innovations.

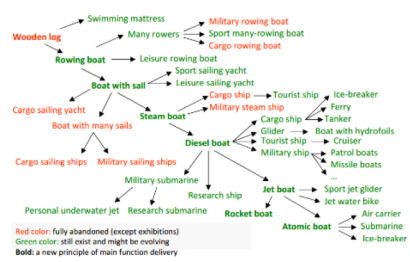
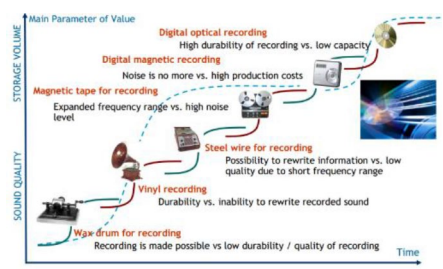
Nine out of the 12 selected ideas are generated in the first 30 min and 8 of them (89%) are generated before 22.5 min, which is approximately half of a design round. Next researches should consider this time frame as a reference for the duration of design sessions in similar experimental activities.

Independently from creative stimulation, approximately 75% and 70% of generated ideas have been scored, respectively, plausible and relevant for a target audience by all 3 experts involved in the assessment. From the perspective of the development of a serious game, which is the future evolution of this study, these results suggest that higher efforts should be invested in the improvement of R&D engineers' performance about novelty.

Comparing the effects of stimuli on R&D designers' performance against each other, trend and patent showed a more positive effect in increasing almost all design proposal characteristics (novelty, relevance and technical plausibility) with respect to the engineering procedure. Therefore, creative stimuli in the form of precedents appear to be better candidates for the implementation in the mechanics of a serious game to support R&D engineers to ideate candidates for the next generation of technical systems. In addition, the results showed that structured precedents as trends appeared to be more effective, compared to singular precedents (patents) for idea generation. This is confirmed considering both the overall quantity of generated ideas and the subset of candidate ones. Moreover, this kind of structural precedents provided evidence to be the most effective in reducing the drop of generativity with reference to novelty, technical plausibility and relevance. This, in turn, has a twofold consequence. For what concerns the research in design creativity, this triggers the need to carry out further studies (with new and fresh large dataset) to compare the effects of structured and singular precedents, as the results of this study substantially show an opposite behaviour compared to what recorded by Doboli and Umbarkar (2014). On the other hand, differently from the engineering procedure, which has just a structured textual set of instructions to follow, both trends and patents were both in textual and pictorial form. This shows a substantially increased effectiveness of the latter (regardless of their nature: structural or singular) against stimuli exclusively provided in a written form. However, an engineering procedure, by its own nature, is intrinsically triggering convergent thinking, so that a lower number of generated ideas is expected through its use. On the contrary, it is expected to be highly efficient in generating ideas of high quality (regardless of the metrics adopted). It is also worth recalling that the experimental dataset is based on the performance of professionals, which constitute a significant difference with reference to most of the considered literature contributions, as experiments were typically carried out with students. Given the higher productivity of the free ideation, compared to the lower performance of R&D engineers invited to follow an idea generation procedure, the game dynamics should be capable of leveraging the already owned skills, rather than constraining the train of thoughts according to strict rules, which appear inhibiting an effective stimulation of creativity.

Besides, all the subjects participating in the experiments were from Iran. This potentially introduces a bias for the evaluation of idea generation performance, as the outcomes reflect a mindset that is potentially influenced by subjects' culture. However, the repeatability of the proposed approach enables the authors and other scholars to repeat similar studies using the same experimental setting and metrics. The results of additional experiments can be, therefore, used to confirm the conclusions of the present study or to highlight potential cultural differences that can be leveraged to fine-tune methods and tools on specific target beneficiaries. Further studies should be also focusing on the nature of pictorial and textual communication of stimuli of different nature, thus including those sources of stimulation that are not based on precedents.

## Appendix 1: Simple evolution path of five technical systems as the first form of stimulus for improving R&D engineer performances and skills in designing the next generation of technical systems

| No. | Examples | Explanation | Picture |
|---|---|---|---|
| 1 | Eye glasses | To realize convenience and smartness through the following stages<br>Two joint lenses<br>Two lenses with a handle<br>Normal glasses<br>Glasses front open<br>Google eye glasses<br>*Bring available technology into the field |  |
| 2 | Umbrella | To realize better adaption to real conditions by solving the problems through new materials, fields and structures through the following stages<br>Paper parasols<br>Ordinary umbrella<br>Non-symmetric umbrella<br>Big umbrella improved for wind<br>Air umbrella<br>* Bring available technology into the field |  |
| 3 | Boat | To realize evolution in both various application and more efficient usage of energy sources through following stages<br>Wooden log<br>Rowing boat<br>Sailing boat<br>Steam boat<br>Diesel boat<br>Jet boat<br>Atomic boat |  |
| 4 | Voice recorder | To realize evolution on quality of object through following stages<br>Wax drum<br>Vinyl recording<br>Steel wire<br>Magnetic tape<br>Digital magnetic recording<br>Digital optical recording<br>*Improving the technology |  |
| 5 | Coffee maker | To realize evolution on quality of object, adding necessary and complementary processes to the system, and co-ordination with super-system through following stages<br>Pot<br>Pot with handle<br>Kettle to brew coffee with boiled water<br>Kettle to brew coffee with steam<br>Electrical coffee maker<br>Capsules of different tastes of coffee<br>Device for one cup of coffee<br>*Bring available technology into the field |  |

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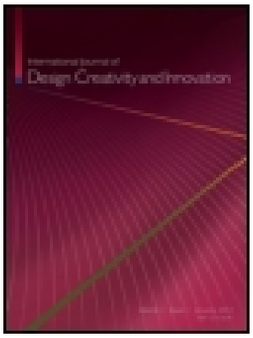

International Journal of Design Creativity and Innovation

ISSN: 2165-0349 (Print) 2165-0357 (Online) Journal homepage: http://www.tandfonline.com/loi/tdci20

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**To cite this article:** N. Becattini, Y. Borgianni, G. Cascini & F. Rotini (2015): Surprise and design creativity: investigating the drivers of unexpectedness, International Journal of Design Creativity and Innovation, DOI: 10.1080/21650349.2015.1090913

**To link to this article:** http://dx.doi.org/10.1080/21650349.2015.1090913

Published online: 20 Oct 2015.

INTERNATIONAL JOURNAL OF DESIGN CREATIVITY AND INNOVATION, 2015
http://dx.doi.org/10.1080/21650349.2015.1090913

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# Surprise and design creativity: investigating the drivers of unexpectedness

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**ABSTRACT**
Scholars argue about the role played by surprise in making new products creative. Different perspectives evaluate surprise as a nuance of novelty, an independent dimension, or an emotional reaction to new products. The paper proposes a framework of factors supposedly characterizing the emergence of surprise in terms of individuals' interpretations and/or modifications of products' behavior and structure. Moreover, it illustrates the outcomes of a preliminary empirical investigation about the manifestation of unexpectedness according to such a framework: the proposed factors have been checked by interpreting the motivations leading to the presence of surprise in 12 new lamps described in the literature. The experiment states the reasonability of the described factors and, as a consequence, the paper provides a contribution to better articulate the debate in the research arena.

**ARTICLE HISTORY**
Received 20 April 2015
Accepted 2 September 2015

**KEYWORDS**
Creativity; surprise; novelty; diversity; emotion



## 1. Introduction

Creativity in engineering design is a complex phenomenon that regards, but is not limited to, people, procedures, products, environments (Thompson & Lordan, 1999). According to the study conducted by Demirkan and Hasirci (2009), products hold the highest importance among all the elements that characterize the creativity of design processes. From this viewpoint, the design community is currently paying significant efforts to establish terms and formalities to assess the creativity of new products or services. Recent proposals suggest some metrics (Borgianni, Cascini, & Rotini, 2013; Sarkar & Chakrabarti, 2011) and discuss the multidimensional nature of the task. However, these approaches base creativity assessments essentially on two terms: novelty and usefulness. Said dimensions are undoubtedly the most acknowledged aspects pertaining to product creativity. Nonetheless, criticism is starting to spread in the literature with respect to the exhaustiveness and the significance of these two factors. For instance, recent studies claim the major relevance of novelty in the evaluation of creativity (Diedrich, Benedek, Jauk, & Neubauer, 2015), also because of the possibly biased interpretation of usefulness in engineering design. This means addressing it with a strictly functional or practical sense, rather than referring to the fulfillment of all kinds of need depicted in Maslow's pyramid, thus including emotional aspects. At the same time, additional factors are supposed to affect the assessment

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of creativity. Gero (2011) points out how surprise is sometimes included within qualitative evaluations, while Brown (2012) urges to investigate such a factor more accurately.

The unresolved conflicts concerning the concept of surprise within creativity are likely to jeopardize any attempt to formalize its computation and subsequent employment. This is especially true within engineering design, while a major understanding has been achieved in other fields. For instance, the emergence of surprise during the design process and the means to generate deliverables arousing unexpectedness are investigated by Dorst and Cross (2001) and Rodríguez Ramírez (2014), by obtaining insights about approaches and tactics of outstanding industrial designers.

Focusing on the open issues about the role played by surprise within the creativity of new products, the present paper aims at better characterizing this concept with a particular emphasis on engineering design. Section 2 documents the debate about the phenomena that enable the display of people's surprise, the influence of such a perception to the extent of creativity, the mutual relationships between unexpectedness and novelty. Section 3 discusses the meaning of acknowledged factors influencing design creativity (Product, Process, Person, Press) within situations in which surprise is perceived by an external evaluator. A set of dimensions are proposed in Section 4 that are claimed to characterize surprising artifacts, emerging from empiric observations of available examples gathered from the Internet. Products considered surprising in literature sources are subsequently analyzed with respect to such dimensions (Section 5); the outcomes of this task show that characteristics typifying novelty are insufficient to describe phenomena of unexpectedness. The final remarks are drawn in Section 6.



## 2. Related art

The present Section illustrates how the literature about creativity and design has discussed the theme of surprise. Reference definitions are provided at first and, then, the review outlines different views with respect to the supposed prerequisite of creative products to arouse surprise.

### 2.1. Surprise: definitions and fundamental concepts in creativity literature

In Section 1, the words "surprise" and "unexpectedness" have been employed with the same meaning. The possibility to interchange the terms is somehow supported by the literature, whereas the most common definition of surprise consists in the violation of expectations. Brown (2008) and O'Quin and Besemer (2006) explain how surprising products present unexpected information to the evaluator. In other terms, they seem implausible or even impossible to be embodied and developed according to current knowledge, generating a sense of astonishment and bewilderment (Boden, 1996). In this perspective, it is worth noticing that surprise does not arise just when expectations have been contravened, but also in those events for which no clear expectation has been formulated (Ortony & Partridge, 1987). At the same time, the extent of surprise is qualitatively linked with the degree to which a transformed aspect of the product is deemed usual, typical, or even immutable (Brown, 2012). Major insights about the kinds of violated expectations are described in (Grace, Maher, Fisher, & Brady, 2014) with the aim of assessing surprise on the basis of the likelihood of infringing habits. Although rooted in the creativity field, the above explanations do not clarify how the emergence of surprise affects the perception of creativity. It is clear that radically new products or unprecedented proposals can lead to surprise. In other words, surprise can take place when novelty is ensured, i.e. whereas one of the most acknowledged dimensions of creativity is manifestly displayed. Hence, with respect to the supposed overlapping of the concepts undermining "surprise" and "novelty," two diffused different visions can be extrapolated from the literature:

- surprise is a particular characterization of novelty, or even a well-identified level of the same dimension (see Subsection 2.2);
- surprise is an independent factor, which can however take place when the product is novel in a certain context and according to a definite background (see Subsection 2.3).

Other perspectives are documented in Subsection 2.4. Subsequently, Subsection 2.5 points out the specific objectives of the work.

### 2.2. Surprise as a characteristic of novel products

As already remarked, novelty and usefulness (sometimes indicated as quality, meaningfulness, or value with similar meanings) are the most diffused terms to evaluate or rank creative ideas and products (Oman & Tumer, 2009). When the concept of surprise has been firstly introduced, it has been typically considered as a nuance of the former. Hoffmann, Cropley, Cropley, Nguyen, and Swatman (2007) report how, in the seminal studies performed by Bruner (1962), the concepts of novelty and surprise even overlap.

More diffusedly, surprise is considered as a degree or a particular cluster of novelty (Chiu & Shu, 2012). This assumption is made also in formalized procedures to evaluate creativity, such as Creative Product Analysis Model, in which surprising solutions are a particular category of novel products (Besemer, 2000). According to this model, novel products are indeed grouped into surprising and original artifacts. According to (Besemer & O'Quin, 1999) original ideas are unusual or infrequently seen in a universe of products, while the surprise component is related to reactions to unexpected or unanticipated information. Additional characterizations are added in later publications, consisting in style (Horn & Salvendy, 2006), i.e. the degree to which a product combines unlike elements into a coherent whole, and germinability, i.e. the driver for suggesting future creative products (O'Quin & Besemer, 2006).

### 2.3. Surprise as a separate dimension

Boden (1996) points out that creative ideas are surprising in essence. However, few studies include surprise as a prerequisite to obtain creative products or a separate dimension to assess them. According to Maher (2011), the difference between novelty and surprise stands in the reference artifacts or concepts against which to compare. While the former emerges when the new product differs from the existing descriptions of artifacts, the latter ensues when deviations are observed from the expected projection of design values and features that belong to a definite conceptual space (Maher, Brady, & Fisher, 2013). In other words, novel deliverables are essentially unprecedented, while surprising ones deviate from the trajectory drawn by a family of products. On the same wavelength, the scholars introduce a binary scale to distinguish surprising and predictable products, by including in the former:

- the ones showing new attributes if compared with the items known in the recent past (Maher, 2010);
- the ones whose performances represent outliers in a time-dependant function, obtained through a statistical regression analysis (Maher & Fisher, 2012).

Nevertheless, the proposed approach can be currently considered as a preliminary proposal to include surprise in the relevant dimensions of creativity, because of the lack of an appropriate validation activity. Besides, other scholars individuate surprise as an independent factor of design creativity, but their purpose is limited to the building of a theoretical framework (Nguyen & Shanks, 2009) or to qualitative evaluations extrapolated from testers' reactions to new artifacts (Goodwin et al., 2013). The assessment of surprise is further complicated by the issue raised by Bruner (1962), who observes the temporary nature of unexpectedness, which quickly ceases after the initial so called "Aha! moment."

### 2.4. Other interpretations of surprise within product creativity

According to different views, surprise does not pertain to the product level of creativity, being it considered as an emotional reaction to different phenomena. Wiggins (2006) explicitly denies the

unexpected dimension of creative artifacts, by considering surprise an emotional reaction of people as a consequence of novelty or outstanding value. Similarly, Silva and Read (2010) focus on the display of surprise as a resultant of products' creativity, but, from their viewpoint, novelty is the unique source of the phenomenon. This vision is partially shared by Burns (2015), who describes, however, a more tangled interplay between surprise, novelty, usefulness and esthetics.

In a different context with respect to engineering design (Information systems), Dean, Hender, Rodgers, and Santanen (2006) individuate surprise as a dimension that, together with rarity, enables the display of original concepts. The link between surprise and rarity refers to (Horvitz, Apacible, Sarin, & Liao, 2005) too.

Eventually, Im, Bhat, and Lee (2015) take into account novelty and usefulness as constituents of artifacts' creativity, but argue that such dimensions are ineffective to ensure future market success. Indeed, the scholars show the relevance of an additional factor, i.e. coolness, to make products attractive or exciting. Coolness is contextually meant as the capability to arouse positive surprise, whereas the mere presence of novelty can lead to the design of absurd deliverables. Recent studies, still in the market field, emphasize the search for surprise as an attracting factor to get people's attention and achieve market success; Hutter and Hoffmann (2014) discuss unexpectedness of advertising ambiences.

### 2.5. Open issues and objectives of the work

The proposed overview elucidates how the concept of surprise is intrinsically connected with design creativity, but several aspects are not shared by the scientific community. In essence, surprise can be interpreted as a characteristic of novel artifacts, a fundamental facet of creative products or an emotional reaction to original and valuable designs. A deeper knowledge about surprise is hence required, especially with regard to engineering design and within the perspective of evaluating the creativity of new ideas and products. The possibility to recognize and assess the determining factors of creative design outputs is a prerequisite for establishing the contribution of these measures to achieve market success.

According to the above open issues, the objectives of the present paper are thus:

- identifying and verifying the existence of distinguishing traits of surprise that are overlooked by most of the schemes of product creativity, which limit their scopes to novelty and usefulness;
- provide a major understanding about phenomena related to the perception of surprise, in order to enhance the available models for assessing design creativity and, in the long term, predicting the potential of new products in terms of market appraisal.

## 3. Rhodes's 4Ps of creativity and their meaning in surprise emergence

### 3.1. Original formulation of Rhodes' 4Ps

Consistently with the different contributions highlighted in Section 2, it clearly comes out that the emergence of surprise can be also characterized by the 4Ps of Rhodes' dimensions of creativity. The scientist collected several definitions of creativity that

> are not mutually exclusive. They overlap and intertwine. When analysed as through a prism, the content of the definitions forms four strands […]. One of these strands pertains essentially to the Person as a human being. Another strand pertains to the mental Processes that are operative in creative ideas. A third strand pertains to the influence of the ecological Press on the person and on his mental processes. And the fourth strand pertains to ideas. Ideas are always expressed in the forms of either language or craft and this is what we call Products (Rhodes, 1961).

More in detail, the different definitions he analyzed and that support the emergence of the Person strand deal with the traits of the individual who is deemed to be creative. Very different factors are mentioned, such as personality, intellect, temperament, behavior, habits, attitude, and some that may even sound unexpected, as physique and traits. The Person is here considered as the actor who is creative, hence the designer, or the problem solver, in the perspective of design creativity. In other terms, the Person is represented by the individual who is asked to provide novel ideas to attain a target goal.

**Table 1.** Essential comparison between the original 4Ps Rhodes' model and the authors' interpretation in the perspective of surprise evaluation.

| 4 Ps | Rhodes' perspective | Authors' perspective |
|---|---|---|
| Product | The final outcome of the design process (as a target for the designer) | The final outcome of the design process (as an object/ idea to be evaluated) |
| Press | The environment and the seeded knowledge in which the design process takes place | The environment and the seeded knowledge in which the evaluation process takes place |
| Person | The designer | The evaluator (e.g. the user) |
| Process | The cognitive process leading from a problem to a solution | The cognitive process through which surprise arises (not considered in this study) |

The Process strand concerns the different activities the Person carries out when she/he is creative. Process deals with very different actions, such as motivation, learning, thinking, communicating, problem solving, etc.

The Press is the "relationship between human beings and their environment." Rhodes wrote that there are forces that push novel needs both inside and outside the Person. Sensations and perceptions, for instance, can come from both internal and external sources. Besides, the Person is exposed to external sources of knowledge and information, including sensory ones, which influence her/his behavior and cognition. For instance, an overload of information may reduce the capability to memorize concepts, as well as to recall and shape idea. On the other hand, Rhodes borrows the words of Gilfillan to clarify that the Press acts as a positive trigger to creativity due to the information and knowledge it produces: "Inventions are not just accidents, nor the inscrutable products of sporadic genius, but have abundant and clear causes in prior scientific and technological development."

The Product to Rhodes is the tangible form of an idea. Products can assume very different forms, such as drawings, words, but also artifacts composed by different materials. Yet, whatever their appearance is, they reflect an idea that has been initially generated as an abstract concept. The idea itself has to be considered as the Product of the creative Process.

### 3.2. Interpretation of Rhodes' 4Ps in the perspective of evaluating surprising artifacts

From the description of these four strands, it emerges that the definition of Rhodes pertains to the designing part of creativity. From his perspective, creativity can manifest into a Product, which has been designed by a Person that followed a thinking Process to generate the idea behind it, under the influence of the Press(ure) for satisfying novel demands due to environmental changes.

The authors share this vision of creativity from the perspective of designing. However, the same four strands appear relevant also from the viewpoint of surprise emergence, even if their meaning needs to be adapted according to the perspective of the individual who senses and evaluates an idea or its embodiment.

This means that the Person to be considered in surprise emergence is not the designing agent, but the evaluating subject (e.g. a user or a stakeholder), whose perception and interpretation of the product (or the idea) might result in a surprised reaction. In this perspective, it is the individual who can be surprised and not the creator of the product. Despite this different angle, the Press exactly reflects the same concept pointed out by Rhodes, since it is the environment by which everyone, even if in different ways, is influenced.

The Product, as well, keeps the same meaning as for Rhodes' description. Indeed, in surprise emergence, the idea that one comes in touch with is the embodied form of the concepts originated by a designer's mind, whatever its form or appearance is.

A significant difference appears on the viewpoint from which the Process can be considered: the creative Process is the one that leads to creative ideas; scholars are still conducting research on effective, efficient, and robust methods and tools to produce such an outcome. As a result, there are just few contributions about heuristics to make this process also capable of coming up with ideas that elicit surprise to the eyes of an evaluator. This kind of creative process still reflects Rhodes' definition.

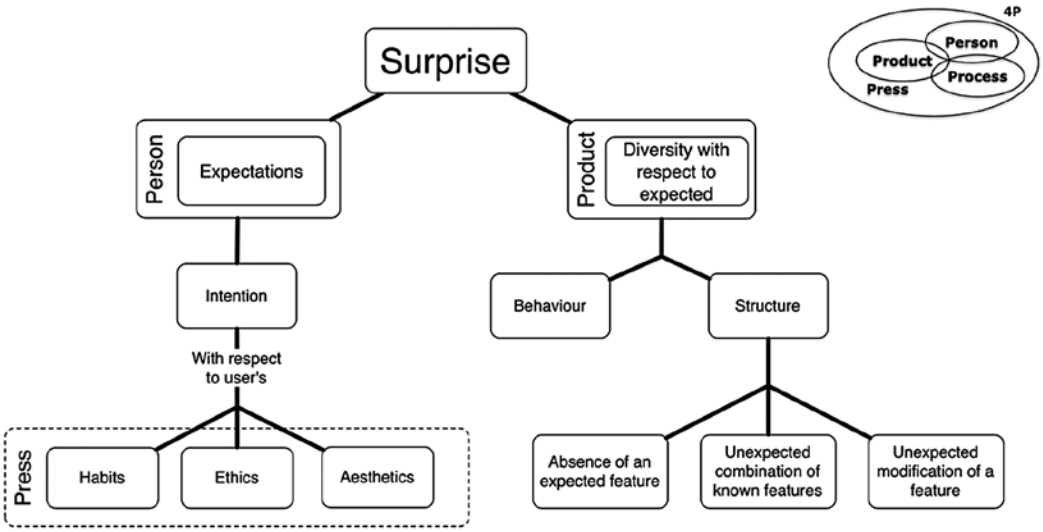


**Figure 1.** The authors' vision about the characteristics potentially triggering the emergence of surprise.

However, it does not pertain to the domain of surprise emergence. The Process concept needs to be redefined here as the cognitive and emotional activities the evaluating subject, more or less consciously, carries out when it perceives a Product and surprise emerges.

The Process will not be considered in the next section, but a preliminary contribution to the characterization of the cognitive processes behind surprise emergence is available in Becattini, Borgianni, Cascini, and Rotini (2015).

For the sake of clarity, the different meanings of 4Ps are summarized in Table 1.

## 4. A model to point out the characteristics of surprising products

Figure 1 proposes the authors' understanding of the potential dimensions triggering surprise. By arising from a deductive process, the model represents a scheme to be tested and further verified, rather than a reference theoretical framework summarizing all the relevant literature contributions.

Indeed, the model depicted in the Figure joins individuated relevant factors, which have been collected by the authors by means of their understanding about the phenomena supposedly determining surprise for a series of original products randomly picked up through the Internet. The articulation of the model clearly reflects the Function – Behavior – Structure ontology (FBS, e.g. Gero & Kannengiesser, 2004), which is well known in the engineering design field and has influenced authors' comprehension of the categories of factors enabling unexpectedness. However, differences can be highlighted with respect to FBS constructs.

On the one hand, the Behavior and the Structure comply with the corresponding ontological entities of the FBS ontology, by potentially dictating the perception of surprise through the display of unexpected peculiarities. More specifically, according to the described adaptation of the Rhodes' 4Ps, there cannot be any surprise if there is no sensorial interaction between a Product (or the idea behind it) and a Person judging it. This implies, on the other hand, that the consideration of the Function deviates from its meaning in the FBS framework, i.e. designers' objective. Indeed, what plays a role in the evaluation of, supposedly surprising, products is the interpretation of the objective set during the design process, mediated through senses and individual perceptions. Still according to authors' understanding, said perceptions can likewise drive toward phenomena of surprise, as a result of mismatches with expectations that evaluators have shaped in light of the Press in which they are

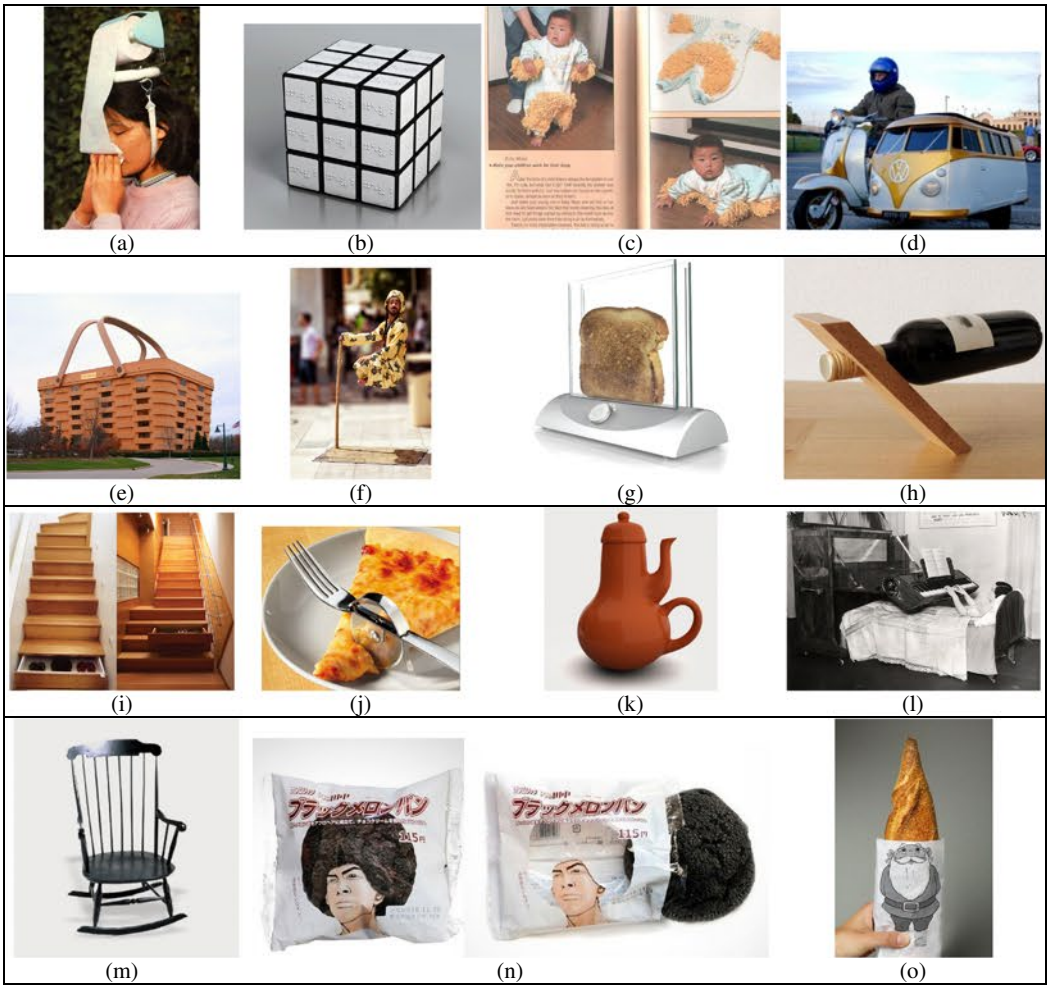


**Figure 2.** Examples of products presenting features directly triggering surprise or inducing surprise by understanding the intentions of the designer.



immersed. Therefore, the Press is constituted by any factor, distinct from the inherent characteristics of the Product, which is capable of dictating the building of an expectation. Ultimately, we can refer to the Press as what exerts social and cultural forces, including individual knowledge, experience, and systems of value.

In coherence with FBS articulation and the required adaptations, the proposed scheme specifies which dimensions mostly pertain to the product itself (here seen as a carrier of surprise by one or more of its features) or to interpretation mechanisms. Examples (pictures collected in Figure 2(a)–(n)), which clarify the meaning of surprise drivers as described at the end of each branch, will be discussed in the following subsections. The left branch of Figure 1 deals with personal interpretations that trigger an unexpected reaction by violating the set of values owned by the individual (Person) that judges according to the mindset of the context (Press). Conversely, the right branch of Figure 1 represents tangible or, more in general, sensible features embedded into the product. It does not mean that the product by itself can be considered as surprising. The personal interpretation of which product features do not match the expectations is still necessary by an observer/evaluator. However, such surprising features are peculiarly embodied into the product.

In these terms, the two main factors characterizing the emergence of surprise are, specifically, the person's expectations and the different features the product owns and that may result unexpected. The former are related to individual- or environment-induced system of values, while the surprised reaction depends on the person's mindset. More gladly such a reaction will be perceived, the higher the matching of surprise with values and beliefs, beyond the degree of mismatching with expectations.

### 4.1. Surprising intention as perceived by the person

This dimension of surprise deals with the interpretation of the intentions underlying a "proposal," as perceived by people. More precisely, a person might get surprised by the mismatch between his interpretation of the motivation behind a certain product or feature and his expectations in the specific context the product in which it is immersed.

Such mismatching may deal with, at least, three main domains:

#### 4.1.1. Habits

Match/Mismatch with social routine, with what is familiar/unfamiliar in a given context or, as well, with events that are more/less frequent to the eyes of the evaluator. Such a specific factor mirrors the findings of the above-mentioned probabilistic approach to evaluate the extent of surprise (Grace et al., 2014). An essential component of the surprise that the toilet roll hat (Figure 2(a)) might provoke is certainly linked with the unexpectedness to show the use of a toilet device in public. It may happen, as well, that something conventional, such as embedding Braille characters to aid visually impaired people, appears as surprising on a certain product (such as Rubik's Cube, Figure 2(b)), due to the lack of specific habits.

#### 4.1.2. Ethics

Match/Mismatch with the concept of "morally right and wrong" in a given context. The suite that makes a baby a mop (Figure 2(c)) generates surprise also because it contrasts what people might consider fair. Besides, despite it being considered right to provide support to impaired people, the above-mentioned example of the Braille Rubik's Cube might generate surprise at first sight. Is such surprise diminished, or at least vanishes more quickly due to the alignment with the ethical expectations?

#### 4.1.3. Esthetics

Match/Mismatch with the perception of beauty, with what is considered nice or ugly. Surprise can be provoked by acting on esthetic standards, as witnessed by examples such as the sidecar in Figure 2(d) and the Longaberger headquarter building in Figure 2(e). In both cases, something with a well-known and appreciated look is proposed out of context, but with opposite outcomes. Indeed, as far as most people describe the former as nice, the latter appears in the top positions of several rankings on the ugliest buildings ever. Such out-of-context proposition of esthetic features can bring surprise to people, but it is required to investigate further to which extent unexpectedness is influenced by the personal perception of beauty.

### 4.2. Surprise deriving from product features diversity

The mismatch between the product features and the related expectations may also depend on intentionally designed product characteristics. These specific characteristics are articulated as shown in the right branch of Figure 1.

Such features can occur at two different levels: the way the system works (Behavior) and what the system is made of (Structure). It is worth noticing that these two aspects can be also mutually tangled, since a change occurring at a structural level may impact on the behavior and vice versa. For instance, an invisible (to the interacting people) structural change may result in a sensibly different behavior for an existing and known product. The floating man (Figure 2(f)) surprises at a first glance because it seems to behave against the laws of physics (or in popular terms, he is not affected by gravity) and

intuition suggests that some structural element is missing. On the other hand, one cannot even imagine at first what the transparent toaster (Figure 2(g)) is used for, since the structure does not resemble any domestic appliance. Then, while it is working, surprise might arise because of the difficulty to imagine how it toasts bread.

Structural changes can be also characterized into further details. Surprise, indeed, can be triggered by structural rearrangements of different types, as proposed hereinafter.

#### *4.2.1. Absence of an expected feature*

A typical source of surprise is the lack of a component or a feature that is definitely expected in a certain product. In addition to the above-mentioned floating man (Figure 2(f)), another well-known example is the wine hold that leverages the mass of the wine bottle to stand (Figure 2(h)). The absence of an expected feature is likely to trigger also a wrong interpretation of the system behavior.

#### *4.2.2. Unexpected combination of existing features*

A product feature is matched with another one coming from a different system or context and such a combination is unexpected. The stairs with hidden drawers (Figure 2(i)) and the cutting fork for pizza (Figure 2(j)) are two examples of this category. It is interesting to notice that, in the former, the feature combination emerges only when the added (surprising) feature is used, while, in the latter, it is visible at first sight.

#### *4.2.3. Unexpected modification of a feature*

A feature is modified (Change) and its specific change is unexpected. More in detail, the unexpected change of a feature may deal with the followings:

- Its aspect or aspect ratio within the product, as for the already mentioned sidecar in Figure 2(d) and Longaberger building in Figure 2(e);
- Its absolute or relative position within the product, as for the well-known "Coffeepot for masochists" (Figure 2(k)), where the surprising placement of the handle and the spout appears as without any logic. Besides, a logical arrangement of features can also result surprising, if non-conventional and unexpected. An example is the piano in Figure 2(l), conceived for those who cannot get out of bed, but difficult to contextualize if seen in a living room with no beds. Also the laterally rocking chair (Figure 2(m)) belongs to this category and it is likely to deliver surprise, especially if an absent-minded user sits on it without noticing the difference and starts rocking. In turn, it is interesting to notice that this surprising features rearrangement may bring to the impossibility to use the object (the Coffeepot for masochists), to the use of the object also by people who would be normally unable, or just to an unconventional usage mode (the laterally rocking chair);
- The perceived meaning of structural characteristics, thus shifting the usage of the product itself to something different, as for the Japanese Pastry Packaging in Figure 2(n). In this case, the dark hair of the character on the package is actually the chocolate pastry itself and, therefore, the surprise emerges when the pastry is pulled out. Another example is the Gnome Bread Packaging (Figure 2(o)), where the bread tip sticking out of the package is surprisingly interpreted as the gnome hat.

## 5. Preliminary verification of the model and discussion of the results

The combination of concepts extracted from literature and empirical evidences about surprising products enabled the identification of surprise arising factors. However, the research approach followed by authors did not ensure the completeness of outcomes in terms of representing all the relevant triggers determining surprise. This issue is deemed important by authors since the exhaustiveness of the proposed framework strongly affects its reliability and future usability to codify users' reactions in front of supposedly surprising or creative products. Therefore, a verification has been carried out to provide preliminary answers to the following questions:

(1) Are the factors encompassed by the model consistent and really capable of mapping the aspects characterizing surprise manifestation?
(2) Besides the already considered ones, does the framework neglect other potentially relevant aspects?

### 5.1. Organization of the questionnaire

The verification was performed through a test planned as follows:

- a sample of odd and potentially surprising products has been identified;
- a respondents sample has been asked to judge and assess the "suprising" products by answering to a specifically developed questionnaire.

Hereinafter, further details are given about the above-summarized activity and collected results.

#### 5.1.1. Respondents sample

The sample is constituted by a total of 23 Ph.D. Students, Researchers and Assistant Researchers coming from Politecnico di Milano, Free University of Bozen/Bolzano, and University of Florence, whose expertise belongs to the field of engineering and design. No information about the framework presented in Section 4 has been shared with respondents before the test.

#### 5.1.2. Products sample

The products sample is constituted by 12 items from the lighting industry, and more specifically lamps. The authors chose this sector for the large availability of examples widely acknowledged as uncanny and bizarre. In order to clarify the peculiar features constituting each lamp, a textual description has been provided to respondents together with some pictures. The whole products sample is reported in Appendix 1 as submitted to respondents, including descriptions and pictures matching the artifacts. The sources for the illustrated surprising lamps and descriptions are (Grimaldi, 2008; Ludden, Schifferstein, & Hekkert, 2008; Rodríguez Ramírez, 2014).

#### 5.1.3. Administered questionnaire

The questionnaire consists of two parts administered in two different steps. The first set of questions aims to perform the screening of proposed lamps according to the respondents' knowledge and their perception of surprise. The questions constituting the first part are the following:

(a) Do you know this lighting device? If Yes, go to question (b), otherwise go to question (c).
(b) Were you surprised when you got in touch with this lighting device for the first time? Answer with Yes or No. If Yes, go to question (d). If No, move to the following product.
(c) Do you believe that this kind of lighting device is surprising or does it present unexpected properties? Answer with Yes or No. If Yes, go to question (d). If No, move to the following product.
(d) If Yes, describe why

The second part of questions leads the surprised respondent to explain personal reasons behind surprise emergence, according to the influencing factors already highlighted by the suggested framework. In addition, a final open question asks to address further reasons triggering surprise. In such a way, the questionnaire helps discover surprise-impacting factors that are not taken into account by the framework.

Furthermore, as remarked in Section 4, some product features might be perceived as negative or positive by people, so generating surprise. This evidence seems particularly relevant for characteristics that belong to Habits, Ethics, and Esthetics categories. Therefore, the questions investigating these aspects have been performed by considering the dual kind of perception that determines surprise.

Eventually, the questions have been administered in a random order to avoid any possible bias effect. Table 2 shows the second part of the questionnaire.

**Table 2.** Second part of the questionnaire: questions investigating surprise triggering factors.

| Factors triggering surprise | Question: I find/found it surprising because it does |
|---|---|
| Habits | (1) Focus on current people's habits and attempt to take them to the extreme |
| | (2) Infringe seeded habits |
| Ethics | (3) Emphasize ethical values |
| | (4) Violate ethical values |
| Esthetics | (5) Stress current esthetical tastes or look extremely good |
| | (6) Mismatch with diffused esthetical tastes or look particularly ugly |
| Behavior | (7) Work or behave in an unexpected way |
| Absence of an expected features | (8) Not include something in its structure I'm used to see or perceive |
| Unexpected combination of known features | (9) Combine something in its structure I'm not used to find together |
| Unexpected modification of a feature | (10) Change something of the structure in a way I wouldn't expect |
| *Other reasons* | (11) Write here |

**Table 3.** Results of the screening: number of surprised respondents for each assessed product.

| Product | Number of respondents |
|---|---|
| On edge lamp | 17 |
| Lamp on/off | 8 |
| Fisherman's tears | 14 |
| Euro-condom | 7 |
| Fly lamp | 6 |
| Titania lamp | 8 |
| Levitating lamp | 21 |
| Leaf lamp | 8 |
| WS/lamp angel | 8 |
| Porca miseria | 11 |
| Flex lamp | 10 |
| Konko | 6 |



### 5.1.4. Results

The results of the test are shown in Tables 3 and 4. More precisely:

- Table 3 summarizes the number of surprised respondents for each product;
- Table 4 presents the following outcomes:

- The number of factors that determined respondents' surprise for each product, already considered by the framework (rows from 1 to 10 of Table 2, which are reported in corresponding columns in Table 4);
- The number of surprising aspects addressed by respondents that seem neglected by the proposed model (column "OTHER").

## 5.2. Discussion on the preliminary results

Despite the sample of people invited to respond to the questionnaire being still limited, the results of this first survey show that the proposed model seems suitable to represent the dimensions characterizing the emergence of surprise.

At first, it should be noticed that:

- all the lamps were considered surprising by at least 6 of the 23 respondents, meaning that they all trigger surprise to a certain number of people;
- surprise is motivated by the respondents through several complementary factors that fall into the list of dimensions proposed by the authors in large majority;
- none of the proposed factors have been considered irrelevant by all the respondents, meaning that all of them appear as influential for triggering surprise in some circumstances;
- some respondents indicated other factors, not included in the proposed list as relevant for inducing surprise.

**Table 4.** Number of answers to the second part of the questionnaire. The numeration of surprising factors and related questions refers to Table 2.

| Surprising factor | Habits | | Ethics | | Esthetics | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Question | (1) Emphasise | (2) Violate | (3) Emphasise | (4) Violate | (5) Emphasise | (6) Mismatch | (7) Unexpeced behavior | (8) Absence of an expected features | (9) Unexpected combination of known features | (10) Unexpected modification of a feature | Other factors |
| On edge lamp | 9 | 13 | 0 | 2 | 1 | 0 | 17 | 14 | 9 | 4 | 1 |
| Lamp on/off | 4 | 4 | 0 | 0 | 2 | 0 | 8 | 8 | 5 | 3 | 0 |
| Fisherman's tears | 0 | 1 | 1 | 0 | 13 | 1 | 3 | 9 | 7 | 8 | 4 |
| Euro-Condom | 1 | 1 | 2 | 0 | 2 | 1 | 4 | 5 | 0 | 7 | 0 |
| Fly lamp | 1 | 0 | 0 | 0 | 4 | 2 | 0 | 3 | 1 | 4 | 1 |
| Titania lamp | 2 | 1 | 0 | 0 | 2 | 3 | 6 | 5 | 2 | 5 | 1 |
| Levitating lamp | 5 | 10 | 0 | 1 | 10 | 0 | 21 | 19 | 15 | 3 | 1 |
| Leaf lamp | 1 | 2 | 0 | 0 | 2 | 1 | 7 | 6 | 6 | 2 | 0 |
| WS/lamp Angel | 3 | 1 | 1 | 0 | 1 | 2 | 6 | 6 | 1 | 6 | 1 |
| Porca Miseria | 2 | 2 | 0 | 0 | 9 | 1 | 0 | 3 | 3 | 5 | 3 |
| FlexLamp | 0 | 4 | 0 | 0 | 1 | 0 | 6 | 10 | 0 | 4 | 1 |
| Konko | 2 | 2 | 1 | 0 | 5 | 1 | 2 | 3 | 1 | 2 | 0 |
| Total answers | 30 | 41 | 5 | 3 | 52 | 12 | 80 | 91 | 50 | 53 | 13 |

The last point would imply that the proposed model misses to represent some aspects that can produce surprise in an observer. Nevertheless, in all the 13 cases registered in this survey, the explanation provided by the respondents seems not related to a factor inducing surprise, but rather to further considerations or judgements expressed by testers. Indeed, exemplary replies to the question "What are the other reasons that surprised you?" are:

- "The atmosphere it produces is wonderful," or "(It) Recall(s) fascinating memory," which seem another way to express what is proposed in factor (5) (see Tables 2 and 4);
- "(It) Changes lighting features continuously," or "it gives a sensation that is not true," which deal with unexpected behavior, i.e. factor (7) (actually, many of the "other factors" appointed by the respondents are definitely explainable in terms of unexpected behavior);
- "It is the only one of these lamps that I would eventually buy," which argues about the outcome of the surprise, rather than about the motivation behind it.
- "When I was 8, I decided that is the lamp that I would like to have in my bedroom. I was searching for colored lights, my parents were not clearly of the same advice. So we found in this lamp the perfect compromise: white light, but with the possibility to change the color of the lamp itself when I wanted to," which points out something that does not deal, at least explicitly, with the factors triggering surprise; it rather provides the rationale behind purchasing choices.

According to the above considerations, the proposed model appears as comprehensive and not oversized, i.e. not referring to irrelevant factors. In fact, Table 4 shows that the answers have been mostly concentrated on specific dimensions while some categories collected just a small amount of records. More specifically, it is worth noticing that both the unexpected behavior and the absence of a feature are often recognized as triggers of surprise (80 and 91 answers, respectively). On the contrary, Ethics has been poorly identified as a critical factor in triggering surprise, even if eight answers witness that some of the lamps represent a surprising violation or reinforcement of respondents' systems of values.

With reference to the validity of the proposed model and its capability to capture the relevant factors triggering surprise, the above two extremes provide significant elements to be discussed. First, the abundance of answers addressing specific factors may lead to consider the existence of sub-dimensions that have not been noticed yet. Second, the model is sufficiently comprehensive to capture also surprising factors which are uncommon, yet existing.

Indeed, especially with reference to the category of Ethics, it is important to notice that the small amount of answers should not be considered as an evidence of poor relevance. On the contrary, the authors believe that this is one of the most significant results of the investigation. Lampsare poorly related to ethical issues intrinsically and, in turn, one's ethics is usually not forged or affected by lamps. Then, if respondents to the questionnaire find a lamp surprising because it violates or reinforce their ethical values, this represents an evidence that the model is comprehensive and capable of capturing the relevant factors, even in a domain in which one should not expect that they are particularly relevant. Moreover, it is worth noticing that the 23 respondents represent a quite homogeneous group in terms of cultural values, being they involved with similar roles in academic institutions; a more heterogenous group could help reduce the effects of cultural biases related to ethical issues. From this perspective, still with reference to Table 4, it is important to notice that zeros in some cells show that none of the respondents find a specific lamp surprising according to the some specific factors of the proposed model. Conversely, it is also worth underlining that none of the above lamps can be considered surprising because of a single factor: the respondents pointed out that at least six factors (Fly lamp) contextually contribute to generate surprise to the eyes of an evaluator. Further studies are necessary to determine if some factors are more relevant than others in determining the emergence of surprise. The analyzed set of objects (lamps) though cannot be considered sufficient to draw any conclusion about the distribution frequency of factors triggering surprise, despite the proposed classification appearing as appropriate to launch an experimental campaign with this objective.

On the other hand, for what concerns the factors that collected the largest number of answers, the authors have not identified more detailed triggers concerning the unexpectedness of products. With

regard to the correlations among different FBS ontological domains, the authors have qualitatively observed that a certain degree of correlation exists between the unexpected behavior and the absence of expected features, which should be considered as a structural characteristic according to the proposed model. However, this correlation needs further investigation, because the missing feature of a specific object is not necessarily sufficient to determine a cause-effect relationship triggering the emergence of surprise as due to an unexpected behavior.

Eventually, the answer reported in the last bullet of the above list suggests a potential correlation between surprise and usefulness. The capability of changing light colors through a screen (Titania lamp) is a novel feature that is not just purely related to esthetics. The function of the lamp generates useful outcomes for its user that, by its own word, was positively surprised. This recorded evidence contributes to the debate about surprise and creativity. Besides, from the same answer, it seems that being surprised by the usefulness of an object produces a persistent effect of surprise, which potentially contradicts the sudden nature of surprise as opposed to the supposed persistent nature of novelty. The latter is considered as persistent if referred to something novel for the whole human kind, but it refers to a subjective phenomenon if the evaluation is taken into account of a user that comes in touch for the first time with an object, consistently with the definition of H-novelty and P-novelty by Boden (1996).



## 6. Conclusions and future activities

The paper proposes a set of triggers that are deemed capable of enabling the manifestation of surprise, whose dimensions and causes hold particular relevance in the field of creativity assessment. These drivers of surprise include evident modifications of product characteristics with respect to existing systems in any reference industrial domain. However, said shifts do not seem to justify the display of surprise by themselves. Indeed, the not negligible role played by human interpretation of creative products contrasts with the vision of scholars that see surprise as a mere dimension or measure of novelty.

The experimental results, obtained through a survey on surprise to which 23 respondents answered, do not provide significant evidence about the existence of any unidentified trait triggering surprise that has been not included in the proposed framework. However, experiments with a wider set of respondents and with questionnaires focusing on different types of products will help make this conclusion more robust. Beyond the extended testing activity, the authors aim at addressing the issues that remain unexplored at the end of this research, such as:

- What are the surprising factors designers should leverage, so that a product or a concept can trigger a surprised reaction in an observer more easily?
- Are these factors independent from each other? Are they intertwined?
- Is there any correlation between surprise and other dimensions of design creativity (e.g. novelty, usefulness, etc.)?
- Is there any relationship between the factors characterizing surprise and the customer's perceived value of innovative products?
- What are the effects of cultural biases in the emergence of creativity?
- Is it possible to describe the patterns of surprising products' evaluation from a cognitive point of view?
- How cognitive factors and emotional statuses of the evaluator interplay?

Larger the set of respondents participating the future testing activities, more precise and statistically significant the results of the above-mentioned investigation activities will be.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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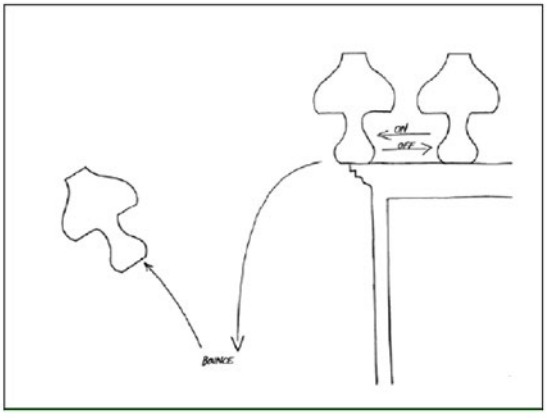
## Appendix 1. The lamps constituting the sample of surprising products for the questionnaire

**On edge lamp**

What is feared of a lamp is that it will fall on the ground and break, and possibly be dangerous because of the glass and electricity involved. To reinforce this fear, the lamp is only on when it is placed on the edge of the table. This creates a sense of suspense, by staging the future fall, and also tends to stimulate people's gut reaction to try to move it to the center of the table. Anyone with children or pets will recognize the tendency to move fragile objects farther from the edge of the table. By moving the lamp onto the table, the user is not only going to touch the lamp, and therefore feel the rubber and realize it will not break, but will also discover that the lamp can only be turned on when on the edge.




The pictures are courtesy of Silvia Grimaldi. For additional information please refer to Grimaldi (2008).

**Lamp On/Off for Luceplan**

The lamp is turned on or off by shifting its weight from one side to the other. The design of the lamp originated as a response to accidentally knocking over the bedside lamp when falling asleep and trying to turn it off. The same kind of gesture can turn the lamp on or off, without knocking it over. For illustrations of the lamp, search images through the string "Lamp On/Off Luceplan" or refer to Rodriguez Ramírez (2014).

**Lacrime del Pescatore (Fisherman's tears)**

A senior lighting designer mentions that in 1975, he saw a fisherman hauling in a net full of fish, and the drops of water falling from the net looked like tears. There was a strong light from the morning sun reflected on the drops. He kept this observation for 35 years and designed the "Lacrime del pescatore" (Fisherman's tears) installation . The design consists of a series of layered nylon nets with 350 crystals representing tears illuminated by a halogen lightbulb.

**Euro-Condom**

A famous designer judges the incandescent lightbulb as 'the most wonderful object made by human beings.' The law introduced in Europe in 2009, which banned frosted incandescent lightbulbs, irritated the designer. His team designed the Euro Condom in response. The design involves a silicon cover that diffuses light just as the frosted incandescent bulbs do.

**Fly lamp**
The designers of this lamp put different animals to the task of affecting their material environment. They also mapped the movement of a fly around a lightbulb in order to design a lamp. For illustrations of the lamp, search images through the string "Fly Lamp Front Design" or refer to Rodriguez Ramírez (2014).

**Titania lamp**
The lamp Titania by a senior designer changes color when the user changes a filter. The designer mentions that the initial intention in designing Titania was to explore the form of a plane's wing. They discovered the property of changing the light's color by experimenting with different materials to decide which colors of plastic the lamp should be offered in. They found that including only one colored sheet of plastic was enough to change the color of the whole lamp, which was an unexpected finding. This was surprising to the designers, who assumed that their customers could be surprised by the same effect too. For illustrations of the lamp, search images through the string "Titania Luceplan" or refer to Rodriguez Ramírez (2014).

**Levitating lamp**
The design is created with what would seem an impossible characteristic that defies the laws of nature. The result is a lamp that levitates. For illustrations of the lamp, lamp search images through the string "Levitating Lamp Front Design" or refer to Rodriguez Ramírez (2014).

**Leaf lamp**
The Leaf lamp features a touch-sensitive area on which it is necessary to run one's finger along the surface of the base to dim the light up or down. There is no visible moving switch. For illustrations of the lamp, search images through the string "Leaf Lamp Fuseproject" or refer to Rodriguez Ramírez (2014).

**Workstation/lamp Angel**
The workstation/lamp Angel uses the form of an archetypal bedside table lamp on a much bigger scale. For illustrations of the lamp, search images through the string "Naos Angel Desk Lamp" or refer to Rodriguez Ramírez (2014).

**Porca Miseria!**
The lamp "Porca Miseria!" consists of broken pieces of expensive porcelain tableware, making it a lamp with a unique shape. Pictures of the lamps "Lacrime del Pescatore", "Euro-Condom" and "Porca Miseria!" are courtesy of Ingo Maurer, www.ingo-maurer.com. Credit: © Ingo Maurer GmbH, Munich, Germany.

**Flexlamp**

The material of the lamp seems a familiar material, but, actually, it is a new material and someone touching it feels different than what he/she was thinking. Indeed, the lamp looks like it is made out of matt glass. Again, it resembles typical glass lamps in shape and surface texture. This lamp is actually made out of flexible polyurethane rubber, and it feels much more flexible than a lamp made out of glass. The pictures of Flexlamp are courtesy of Industrial Facility: www.industrialfacility.co.uk. Design: Industrial Facility / Sam Hecht. Photography: Copyright Industrial Facility.

**Konko**

Alternative or new production techniques can be used to create new shapes for known materials. The lamp is made using a 3D printing technique, creating a new shape for a lamp and for the material, a polyamide. The lamp looks like it is made out of cloth or paper, and may be expected to feel light and flexible. However, it feels solid, heavy, and unflexible. The picture of Konko lamp is courtesy of its designers Willeke Evenhuis and Alex Gabriel.

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Main research interests: epistemology of innovation and design, digital innovation, indeterminacy and technology, innovation management


**Title of the Presentation:**

Conjunctions of Design and Automated Search in Digital Innovation

**Synopsis:**

The increasing availability of comprehensive digital models of manufacturing and other contained industrial operations creates potential to apply automated search procedures for innovation purposes. At the same time, it increases the size and complexity of the design problems, such that deterministic solution approaches are not applicable any more. Using C-K-Design theory, the presentation explores the occurrences of concept and knowledge operations in such scenarios and their mutual dependencies.

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Fritzsche, A. (2018). Implications of agile manufacturing in the automotive industry for order management in the factories - evidence from the practitioner's perspective. *Procedia CIRP, 72*, 369–374.
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**Further readings:**


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Procedia Manufacturing 25 (2018) 161–168

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8th Swedish Production Symposium, SPS 2018, 16-18 May 2018, Stockholm, Sweden

# Increasing the acceptability of plans in manufacturing by transparent search

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**Abstract**

Most planning problems in manufacturing have large solution spaces and require the consideration of various different objectives. Using insights from industry, this paper shows that planning therefore often goes along with a negotiation process about the acceptability of solutions. The paper investigates how this negotiation can be supported by providing additional data during the planning process. It discusses a pilot system for sequencing and scheduling in the automotive industry equipped with a large graphical interface which allows the planners to observe the progress, analyze the consideration of different objectives and interfere with the setting of weights and references wherever necessary.


Peer-review under responsibility of the scientific committee of the 8th Swedish Production Symposium.

*Keywords:* Sequencing and scheduling systems; heuristic search; operative transparency; negotiation; acceptability.

## 1. Introduction

Over the past decades, increasing global competition and demand volatility have turned the attention towards the question how industrial production can become more agile and adjust the output to specific customer needs [1,2]. Modern information technology has made it possible to replace static hierarchies in companies with modular and network-oriented organizational structures [3] and modular product and process designs have enabled mass-customization in manufacturing [4,5]. The automotive industry can serve as a good example to observe the consequences of this development. It has moved from manufacturing identical vehicles in large numbers towards the assembly of individual products from a multitude of different model series, engine variants, colors and equipment

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2351-9789 © 2018 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the 8th Swedish Production Symposium.
10.1016/j.promfg.2018.06.070

options [6]. Although modern factories in the automotive industry need to process huge order volumes every day, they are able to adapt to strongly changing order volumes in short time and thus react very quickly to shifts in the market.

While this constitutes a huge achievement from an engineering perspective, it causes a problem from the perspective of production planning: flexibility in manufacturing comes at a price, as it creates additional effort for parts delivery and storage, varying mounting times, shipment processes etc. The more flexible manufacturing is, the more difficult it becomes to determine how a given order volume has to be scheduled and sequenced in order to minimize the overall costs in production.

On one day, the order volume might allow for the generation of a sequence which takes all criteria in account and produce evenly best results with respect to all cost drivers in the value chain. On another day, such a solution might not exist, but only a few different alternatives which either put cost pressure on assembly, or on the paint shop, or on the supply chain. Order volumes in the automotive industry are so big and diverse that these dynamics remain intransparent. The decision makers in the factories face a new problem configuration each day, and they are unable to predict which kinds of arrangements of the different drivers of production cost can be achieved under the given circumstances, and if it is comparable to the situation they were facing the day before.

Extant research has already looked extensively into the technical possibilities to find good solutions for sequencing and scheduling problems in manufacturing contexts. In particular, heuristic search strategies have received a lot of attention as means to cope with increased complexity which do not allow the application of conventional deterministic solution procedures. Comparably little has been said about the consequences of changing order volumes for the practice of problem solving. These consequences do not concern the technical design of the solution process, but its added value for the organization. In a static environment, all stakeholders in manufacturing can form gradually expectations about what sequencing and scheduling can achieve. If the structure of the solution space changes all the time, this is not the case anymore. There is always a chance that the expectations of some stakeholders will be disappointed by the results, because certain capacity constraints and attributes of the production sequence are not satisfied any more. The situation becomes even worse when heuristic search algorithms are applied which cannot guarantee that best elements of the solution space can be identified. It therefore remains doubtful if the new order volume really does not permit the satisfaction of the criteria or if the algorithm is badly designed and configured.

Under such conditions, the task of the practitioners responsible for order management in the factories assumes a new quality. They are not only responsible for the provision of production sequences and schedules, but they also have to manage the expectations of the stakeholders and explain why the attributes of these sequences and schedules change over time. From the perspective of organizational theory, this can be described as problem of legitimacy, as the practitioners need to provide reasons to make their own work acceptable.

The research interest in this paper is directed at the question how sequencing and scheduling systems can support their users in dealing with legitimacy issues related to their work. To answer this question, the paper takes a design-oriented approach in developing graphical interfaces which make the solution process more transparent. They supply users with additional information about the solution space and allow them certain types of interventions to explore different directions of improvement. The interfaces are presented to practitioners in the field, who provide expert feedback which reveals various insights into legitimacy strategies in order management. These findings hold various implications for further research.

## 2. Theoretical background

### *2.1. Order management in the factories*

Order sequencing and scheduling for production constitutes the last step of planning before the value chain switches from the treatment of mere information to the actual generation of tangible objects. It also marks the point where plans reach their highest level of detail. In the course of the past decades, the automotive industry was able to postpone the finalization of the sequences and schedules to less than a week before production start in the factory of the original equipment manufacturer [7]. Before the finalization, there is a lot of flexibility in the supply network to pursue decoupled planning activities among suppliers, original equipment manufacturers and their sales organizations [8,9]. The experts who are responsible for order management in the factories have to reconcile all these differ-

ent planning activities when they put the sequences and schedules for production together. In such situations, Klaus [10] explains that complexity is accumulated from the whole network (see Fig. 1a, on the left). If order management is not able to cope with this complexity, contradictions appear between the final sequences and schedules for production and earlier plans in the network, which has to be resolved somewhere else (see Fig. 1b, on the right).

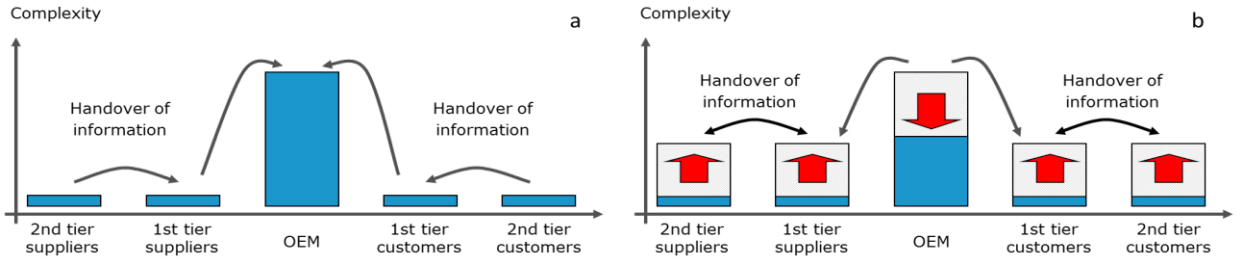



Fig. 1. (a) accumulation of complexity based on prior plans [see 10]; (b) reassignment of complexity which cannot be processed.

There are many different ways how such backward shifts of complexity proceed. For example, one might think of a situation in which order management is unable to fulfil the target dates for order completion agreed with the sales organization without violating capacity constraints from suppliers. At least one of them is therefore forced to revise plans: either the sales organization has to cope with delayed orders or the suppliers have to increase their capacities. Constraints from the shop-floor in the factories regarding workload distribution, additional mounting times for specific orders or color batches from processing similar orders in the paint shop together can also be involved.

While advanced sequencing and scheduling systems are able to consider numerous different constraints during the search for good solutions, they cannot guarantee that all constrains can actually be met on a given order volume, in particular when the orders are highly individualized and the multiple combinations of different attributes relevant for the constraints are hard to keep under control.

### *2.2. Heuristic solution procedures*

Without additional effort for simplification, sequencing and scheduling problems in manufacturing are known to be NP-hard, which means that the processing time for an exact calculation of best solutions grows very fast with increasing order volume [11]. Instantiations of such problems in the automotive industry are further complicated by the complexity of the manufacturing process and the large number of different criteria affecting the quality of the solutions [12]. As a result, advanced sequencing and scheduling systems in industry rely on different kinds of heuristic search algorithms to generate solutions within a reasonable time frame [13,14]. Iterated local search techniques play a particularly important role in this context [15]. Such techniques separate the steps in which solutions are identified from the step in which they are evaluated (see Fig. 2).

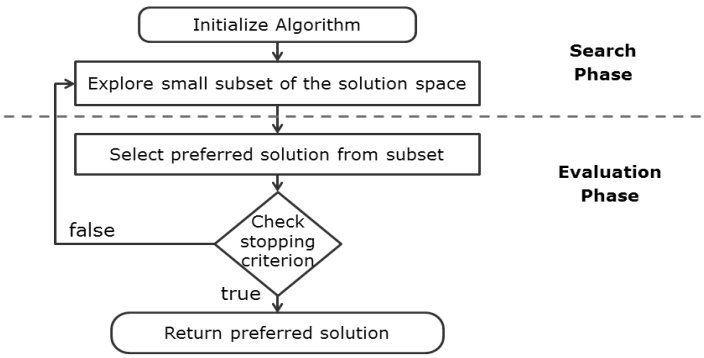



Fig. 2. Basic principle of iterated local search.

This makes it possible to apply them in situations where little is known about the logic behind the evaluation process [16,17]. A very well-known illustration of this principle is natural evolution, where arbitrary changes are subjected to a selection process according to their fitness to survive in the given environment. Different variations of this principle are embodied in numerous kinds of search techniques [18,19].

The performance of these algorithms has been studied on various occasions and with respect to various types of problems which are usually represented by standardized problem instances [20,21,22,23]. Some authors have looked into the possibility of changing the evaluation function in the course of the search, due to interference by a system user [24] or on a purely algorithmic level [25]. Fairly little has been said, however, about the problem of determining evaluation functions under conditions of rational choice with limited access to information [26,27], as they are present when the content of the order volume has a different quality every day.

### *2.3. Legitimacy issues in problem solving*

Order management experts using advanced systems for sequencing and scheduling can be expected to have ample information about the costs related to a sequence for each single criterion, provided by suppliers, production management on the shop floor and sales organizations. Nevertheless, there is no generally valid rule which would determine how these costs can and should be set in relation to each other [28]. Sequencing and scheduling systems usually support one out of two choice strategies: (1) "brute-force" approaches with a hard prioritization of criteria according to a list such that a next criterion in the list is only considered once the sequence has reached an acceptable quality for all previous ones or (2) the calculation of a weighed sum of the cost values for all respective criteria [15]. In addition, decision makers can set reference points for optimization in terms of preferable outcomes, which may or not be reachable [29]. Whatever strategy is applied, it involves decisions by the system's user which are not endogenous in the given situation, but result from his or her preferences. This is the point where a need for legitimation emerges, whenever other stakeholders who are involved raise concerns about the quality of the generated output.

Organizational theory describes such scenarios as problems of legitimacy regarding the actions of the experts using the systems [30,31]. Legitimacy can be generated in different ways. Research distinguishes at least three different approaches [32]:

- Cognitive legitimacy is given when something is comprehensible or taken for granted, such that it appears logically plausible for others.
- Moral legitimacy is given when something appears to be the right thing to do. Moral legitimacy can, among other factors, also result from personal authority or tradition.
- Pragmatic legitimacy is given when something is perceived to satisfy the interests of an audience, on the personal level, department level or company level.

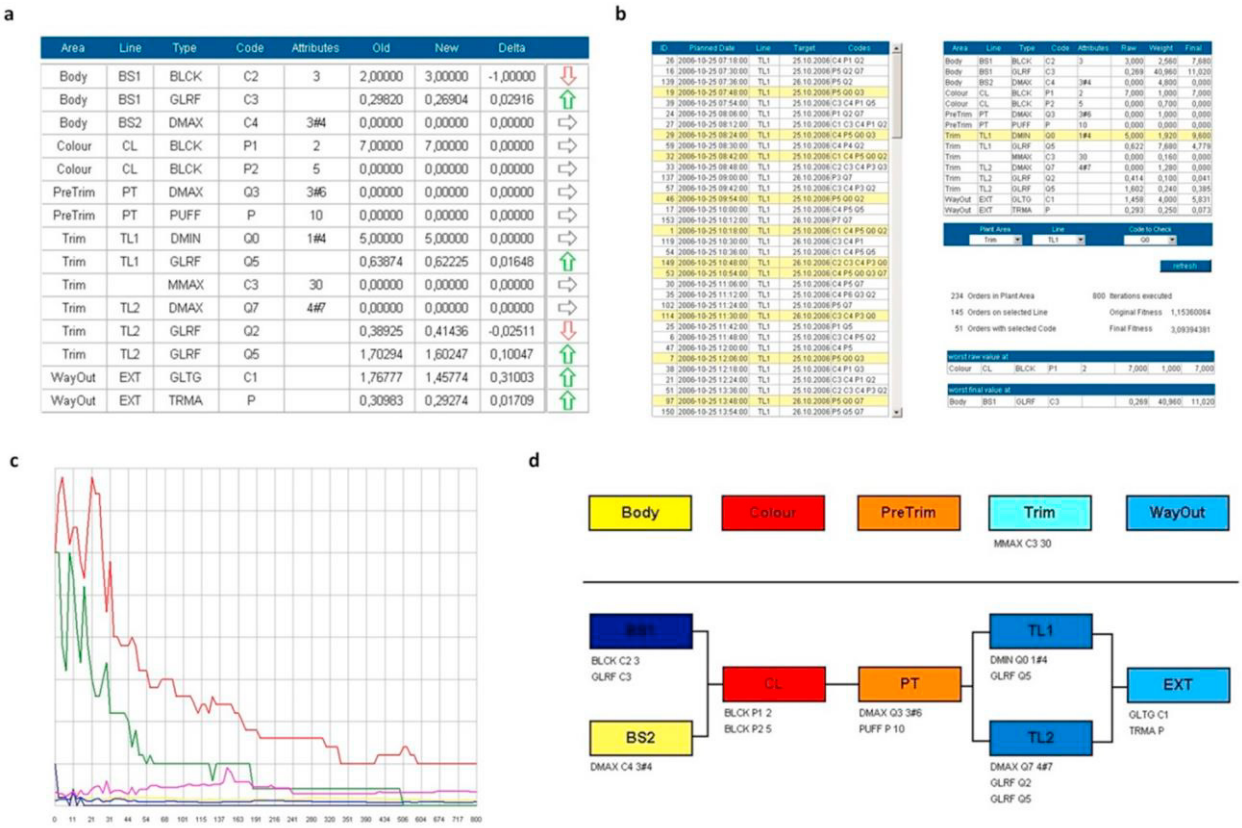
Legitimacy issues in organizations have already been extensively researched by numerous business and management scholars, but they have hardly been connected to issues in manufacturing or systems engineering. In this respect, the paper moves into uncharted territory, since it investigates how legitimacy can be generated in the context of order sequencing and scheduling for production in the automotive industry.

## 3. Research approach and artefact design

The first pages of this contribution have shown that order sequencing and scheduling in the factories is at risk not to satisfy the expectations of all the different stakeholders in the process, such as suppliers, sales organizations and the shop floors in the factories themselves. Furthermore, they have shown numerous degrees of freedom in the choice and configuration of the solution techniques applied in this context, which give other stakeholders reason to question the work of the practitioners who are responsible for generating the sequences and schedules. It is therefore necessary support the legitimacy of their work. This paper investigates the role of the information systems used for sequencing and scheduling for the generation of legitimacy. In particular, it looks at the possibilities to supply users which additional information about the search process which can be used in discussion with other stakeholders.

As a basis for the further exploration of the problem the paper uses a previously implemented system using a heuristic search algorithm for order sequencing and scheduling in the factories under consideration of complex plant layouts, multiple optimization objectives referring to diverse attributes of a given order volume [33]. In this implementation, the search is performed by a genetic algorithm as an iterated process of modifying existing solutions and selecting the best results of these modifications for further treatment in the next iteration. The progress of the search is stored after each iteration in an external database for further investigation at a later point of time. The search algorithm is complemented by another module of the system used for evaluation. It includes a graphical interface which allows users to observe the progress of the search and also to change criteria and their weights during the process if considered necessary. The exchange between these two modules of the system takes place via the data storage units to ensure consistency of the information and traceability of the progress.

The graphical interface provides different views to gain insights in the search process which might play a role in negotiations about the solutions. Fig. 3 and 4 show the different views available in the system.

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| Trim | TL2 | DMAX | Q7 | 4#7 | 0,00000 | 0,00000 | 0,00000 | ⇨ |
| Trim | TL2 | GLRF | Q2 | | 0,38925 | 0,41436 | -0,02511 | ⇩ |
| Trim | TL2 | GLRF | Q5 | | 1,70294 | 1,60247 | 0,10047 | ⇧ |
| WayOut | EXT | GLTG | C1 | | 1,76777 | 1,45774 | 0,31003 | ⇧ |
| WayOut | EXT | TRMA | P | | 0,30983 | 0,29274 | 0,01709 | ⇧ |

Fig. 3. Views to evaluate the search progress available to the users (a-d).

View (a) shows the sequence itself. For each criterion, the relevant vehicle orders can be highlighted to mark their position in the sequence. View (b) shows a numeric evaluation of the criteria with some additional information about the latest development of the sequence regarding each criterion, improvements or deteriorations of quality. View (c) shows the development of solution quality regarding single criteria. As the system measures violations or deviations from the optimal result, improvements go along with a reduction of the value. View (d) shows aggregated values per plant area and line (if parallel production occurs in a plant area). Red colors indicate lesser and blue color higher quality. View (e) aggregates the criteria according to the parties interested in them, which is in here parts supply, production and distribution. View (f) uses block charts to compare the quality for single criteria and overall values per line or plant area. Different criteria can be switched on or off in the display to improve understandability.

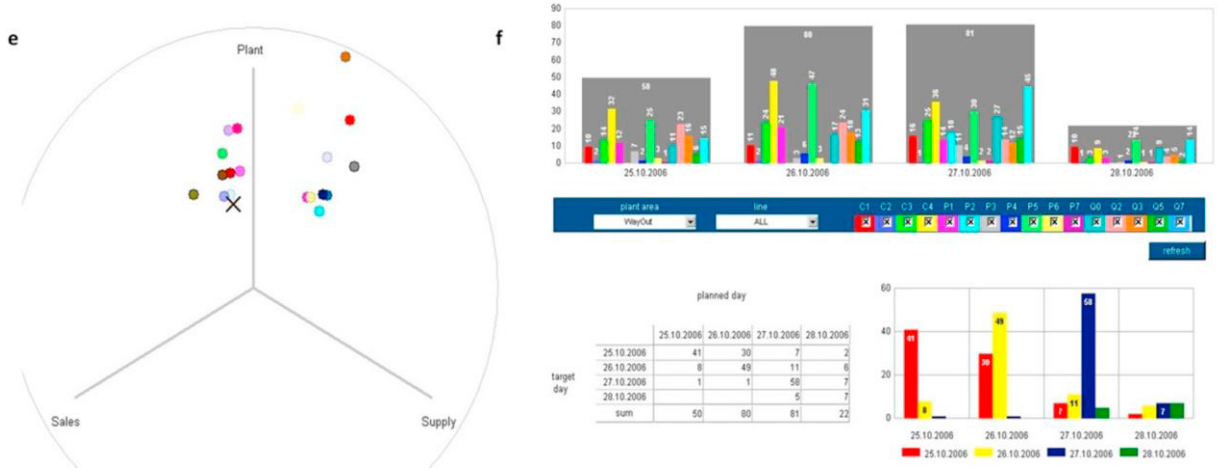


Fig. 4. Views to evaluate the search progress available to the users (e-f).

## 4. Application and Findings

The system was introduced to various experts responsible for order sequencing and scheduling in factories as a prototypical version which could later be further developed for practical application. The experts were then invited to try out the system and discuss ways in which it could support them in practice. Observing them and collecting their feedback yielded the following results:

- The graphical interface was first and foremost understood as a means to gain a better understanding of the order volume which was processed in the system, while the insights into the progress of the search played a secondary role. This was considered helpful by the experts, because it allowed them to explain to other parties how difficult it was to find good solutions, to lower their expectations and to negotiate concessions from them regarding the severity of constraints.
- Changes of criteria and weights during the search process were not so much connected with the intention to gain better results of the search, but instead learn more about interdependencies between the different criteria and the extent of contradiction between them, which could again be used in discussions with other parties involved. Although illustrations were provided how weight changes affected the solution quality, practitioners were not interested in further opportunities to customize the search.
- When asked which view most helpful and which were unnecessary, experts named the charts showing progress over time as their favourites. At the same time, however, they emphasized that they were interested in keeping all views in order to gain as much information by looking at the data from any possible perspective. Only the functions for intervention in during the search process were considered to be of lesser importance by most of the experts and rather expected to serve as a tool for systems design and engineering.

Overall, it can be said that the experts trusted the search algorithm to provide good results and had less interest than expected in deeper exploration of weight changes for single criteria to change the direction of the search. Instead, they focused on the contribution of additional information about the order volume provided by the system. This information was considered to be highly valuable for negotiations with other parties, because it showed the real source of complexity as the experts perceived it: the immense variations in the order set resulting from increased customer orientation.

One can therefore say that the system was seen as a source of data which could provide cognitive legitimacy by making the problem situation and the root causes of all conflicts better understood. It enabled the experts to point their fingers at someone else: the strategists in the company who decided to increase customer orientation or the customers themselves who made so much use of it. In this sense, the legitimacy problems were not resolved, but

only externalized such that they did not concern the stakeholders in the planning process but some other people somewhere else.

Implicitly, the system was also considered to provide moral legitimacy by strengthening the authority of the experts in the discussion. It allowed them to present themselves as the authority in the context of order management with unrivalled competence for decision making. This is also illustrated by the fact that the experts were hardly interested in sharing the system with others, but rather wanted to keep it to themselves, with all possible graphical interfaces to gather information. As an explanation for their unwillingness to share the system, various experts explained that they were the only ones who had no attachment to any specific interest groups. Other parties were suspected to be inclined to abuse the screens to strengthen their own position and make sure that their own requirements received most attention. Order management in the factories was described as a neutral institution to find the best balance between the interests of the different parties involved.

## 5. Discussion and Conclusion

Solution processes for manufacturing problems are usually approached on the background of Taylor's principles of scientific management [34], which are highly suitable in the context of mass production with large volumes of standardized goods. Under such circumstances, drivers of complexity such as volatile demand, customized products and global supply chains can be neglected; wicked socio-economic problems can be tamed down into simplified design tasks for industrial operation which remain sufficiently transparent to capture them in a formal, analytic model which allows the application of fully rational solution procedures [35,36]. Order sequencing and scheduling for production in the automotive industry shows the limitations of this approach in today's customer-oriented, volatile manufacturing environments. While decoupling creates opportunities to tame down other planning problems at earlier points in the value chain, order management in the factories cannot avoid taking all the different drivers of complexity into account in determining the final plan for the fabrication of the ordered vehicles. This makes it necessary to think about solution processes in a new way.

Instances of wicked problems are usually unique. They occur only once in their specific form. Other instances which occur at another point of time look different. As a consequence, problem solvers cannot be sure how much they can rely on prior experience in dealing with them. They can therefore not just blindly apply a given solution procedure. Instead, the solution process requires the deliberation of different objectives and strategies to come up with a result which gives an appropriate account of the present conditions. The solution to the problem is just as unique as the problem itself [37].

This paper has looked at the organizational consequences of the occurrence of such unique problem solutions in a manufacturing context which involves many stakeholders along the value chain. Following extant theory, it has focused on the question how the experts responsible for order sequencing and scheduling in the factories legitimize their work output.

As the root cause of the wickedness in the given scenario is the intransparency of the solution space and the missing information about best choices in sequencing and scheduling, it stands to reason that supplying more information can remedy the problem. The paper has therefore studied how additional information provided by the technical systems used for sequencing and scheduling can add to legitimacy. For this purpose, a graphical interface has been studied which allowed users to observe and analyze the progress and results of the search procedures and even interfere with them in real-time to gain more insights into the underlying dynamic.

Interestingly, the results show that users appreciated the possibilities granted by the interface to gain insight into the content of the order volume, while they did not care so much about the insight it could provide to better understand the actual search procedures performed by the algorithm. Legitimacy issues related to the technology used for problem solving have thus received little attention, although one might expect that the technology leaves ample space for improvement. The investigation of the reasons for this behavior was not part of the study. One might speculate, however, whether this strong belief in the power of the systems has its roots in the traditional division of labor, which made a clear difference between the systems engineers and the users of the system, such that the users did not interfere with the other's work, but just appreciated whatever means were provided to them.

Future research will be necessary to understand the results in more detail and broaden the empirical base for the investigation of the scenario. In this sense, the work presented here can only be considered as a first step into a new direction which might prove to be highly important in further research, as the complexity of manufacturing systems can be expected to increase with an ongoing trend towards customer orientation and individualization.

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Procedia CIRP 72 (2018) 369–374

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51st CIRP Conference on Manufacturing Systems

# Implications of agile manufacturing in the automotive industry for order management in the factories - evidence from the practitioner's perspective

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**Abstract**

Agile manufacturing in the automotive industry increases customer orientation and allows a faster reaction to changing market conditions, but it also complicates the task of sequencing and scheduling orders for production in the factories. This paper provides empirical data about the constraints under which sequencing and scheduling takes place. Based on a formal model in generic terms, it describes order volumes, factory layouts, production efforts and types of quality criteria which are frequently used in practice. It shows that extant algorithmic solution approaches are still applicable under such condition, but need to be reinterpreted regarding their role in the process.



*Keywords:* Production Planning Systems; Multi-Objective Problem Solving; Heuristic Search.

## 1. Introduction

The automotive industry continues to grow. Despite various economic crises during the past decades, the production volume has steadily increased to a number of 94.8 million units worldwide in 2016 [1], with a turnover of several trillions of dollars achieved by the original equipment manufacturers alone. Overall, more than 50 million jobs are believed to depend directly on vehicle manufacturing, illustrating its essential role for the global economy [2]. While the opening of the Chinese market at the turn of the millennium has created new potential for growth which temporarily reduced the competitive pressure on incumbent manufacturers, they are now challenged by Asian companies such as SAIC, ChangAn, Geely, TATA and many others which take increasing shares of the international market [3]. In addition, the automotive industry is swamped by digital innovations and new engine concepts which create further dynamic in the industry [4].

For quite some time, agile manufacturing strategies have been discussed as means to become more competitive [5,6]. Like many others, the automotive industry has in particular looked into the possibilities of postponement to answer more quickly and accurately to changing demand [7]. Platform strategies have played an important role in this context, as they have enabled manufacturers to produce different types of vehicles with the same components. At the same time, however, the variety of models and variants offered on the market has continuously increased [8], such that the number of platforms used by manufacturers is nowadays comparable with the number of different models in the late twentieth century. Overall, platform concepts have therefore not had a significant impact on the reduction of production complexity. They rather seem to have resulted in a shift of diversity from engineering components towards body shapes, parts and equipment options which do not so much affect the basic architecture of the vehicles, but the effort to produce them in the factories.

From the practitioner's perspective, agile manufacturing in the automotive industry is therefore for the most part a matter of diversity and individualization. Customers can nowadays choose between a seemingly endless number of options to configure their orders according to their personal needs and preferences, regarding their shapes and sizes, engines, transmissions, colors, equipment and accessories [9]. For premium brands, customers can also expect that their vehicles are man-


10.1016/j.procir.2018.03.127

ufactured individually for them and delivered within a short time frame, which adds an important aspect of servitization to their purchase of the product [10]. All this is made possible by advanced scheduling and sequencing systems which are able to consider multiple different objectives at the same time.

Scientific research has looked extensively into the design of suitable algorithms for sequencing and scheduling. This paper reflects the problem from a wider perspective by moving the attention towards the question how increased agility affects the perception of the problem itself, i.e. the task which practitioners have to perform in sequencing and scheduling. After introducing the conceptual background, the paper presents an empirical study performed in various factories in the automotive industry. The findings give insight into the size and complexity of the solution space and the different types of constrains which are considered in practice. The subsequent discussion investigates the implications of the findings for the understanding of the problem and the role of algorithmic search to find solutions.

## 2. Conceptual background

### 2.1. Problem description

Extant research on the car sequencing problem addresses the task of scheduling production orders such that they pass through the factory in a sequence that minimizes manufacturing efforts caused by assembly constraints and supply capacity restrictions [11,12]. Various publications connected to the ROADEF challenge of 2005 have drawn particular attention to application cases from the company Renault which focus on workload balancing in assembly and the reduction of color changes in the paint shop [13]. The interest in workload balancing can be explained, for example, by additional mounting times for machines which install rarely ordered parts like sunroofs, whereas color changes cause additional efforts for cleaning the machinery in the paint shop. However, there are many other types of efforts which can be taken into consideration, such as energy consumption in the factory [14,15].

In order to capture the large variety of different aspects of sequencing and scheduling tasks in agile manufacturing, the problem is henceforth addressed in very general terms, based on the usual nomenclature of job or flow shop scheduling problems [cf. 16]. It includes the following constructs:

- A list of production jobs $(J_1 \ldots J_n)$ for production orders $1$ to $n$ which are characterized by a certain body type, color, engine and transmission variants and many different equipment options, a due date on which it is supposed to be handed over to the customer, a destination for delivery, and other attributes.
- A list of machines $(M_1 \ldots M_h)$ and operations $O_{MjJi}$ required for each job $J_i$. at machine $M_j$. In the context of the automotive industry, the jobs can be expected to pass through the machines in the same order, turning the situation in a flow shop scenario. It is not necessary, however, that each job causes efforts at every machine. If there is parallel production, for example, jobs will only cause efforts at machines on one line, but not on the other(s).
- A solution of the problem, e.g. in the form of a permutation $\pi$ of the list $(J_1 \ldots J_n)$, which indicates the production sequence of the jobs. Under the assumption that a factory has a fixed production capacity for each day or shift, each spot in the sequence belongs exactly to one production day and shift, such that all time schedules can be derived from the sequence. The set of all possible solutions is called the solution space $\Pi$.
- An evaluation function $\gamma$ on the elements of $\Pi$ which calculates the overall quality $\gamma(\pi)$ for each possible sequence $\pi$ of orders. This function can be assumed to be an aggregated of single cost functions $\{c_1 \ldots c_k\}$ which calculate manufacturing effort related to operations $O_{MjJi}$. The cost functions either count violations of hard constraints or measure deviations from target values.

The practitioner's task can then be described by the following target condition:

$$min\ \{\gamma(\pi) \mid \pi \in \Pi\} \tag{1}$$

The layout of the production plant determines the list of machines, the possible operations at each machine and the efforts necessary for executing the operations. These parameters can be considered to remain stable over time. All other parameters can be expected to change frequently in agile manufacturing scenarios. Variations in the order volumes affect the operations which need to be executed for a production job. Component updates and changes in parts supply or market demand affect the structure of the cost function and the weighed aggregation.

### 2.2. Solution techniques

Like most shop problems, the car sequencing problem is known to be NP-hard, which makes the application of exhaustive analytic solutions procedures unfeasible [17,18]. Extant literature therefore focusses on heuristic approaches to tackle the problem. While early work on the car sequencing problem has taken a constraint programming perspective [11,12], recent contributions explore other techniques such as ant colony optimization and greedy algorithms [19], simulated annealing and genetic algorithms [20], which are better suitable for the treatment of large solution spaces and complex evaluation functions [21].

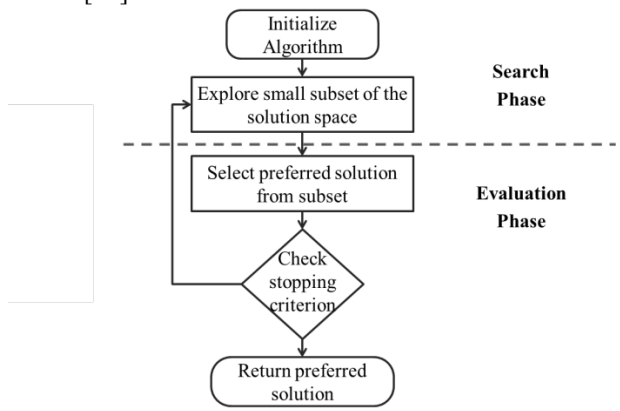


Fig. 1. Principle of iterated search

All these techniques follow the same pattern of an iterated search process (see Fig. 1). Each step explores the solution quality which can be achieved "locally", i.e. on a small set of possible alternatives defined according to certain topological criteria. Based on the insights gained from this exploration, a preferred solution (or a set of such) is memorized and the process moves on to explore another set of alternatives in the next step, and continues to do so many times until a given stopping criterion is satisfied and the search ends.

A characteristic feature of this approach is the relative independency of search and evaluation. Evaluation criteria can therefore be provided by a so-called oracle: a black-box component providing a statement about quality without explaining the whole rationale behind the evaluation or indicating ways how a solution might be improved. As a consequence, the abovementioned techniques are robust against changes of the problem parameters. Formal considerations, however, show that situations exist in which changes lead to a decline of efficiency in the performance of the algorithm [22,23]. If this was not the case, the problem would not be NP-hard.

Solution techniques based on iterated search therefore remain applicable in scenarios with increased agility. To ensure performative efficiency, however, changes in their configuration might become necessary [24]. Such changes can concern the search phase or the evaluation phase of the algorithm. Extant research suggests that the usage of operators during the evaluation phase which are sensitive to changes of the solution space is a suitable means to cope with agility [25].

## 3. Research design

Having clarified the conceptual background, the paper now moves to the empirical study of the actual problem instances in the practice of sequencing and scheduling in the automotive industry. The focus is set on factories where vehicles on the upper end of the quality and price range are produced, because they can be assumed to be more affected by diversity and individuality than the mass market and therefore give more insight into the dynamics of agile manufacturing. The study is intended to contribute to a better understanding of the challenges connected to the practitioner's task in the factories and the ways how they can be expressed in formal terms.

The factories considered in the study are located in Central Europe (Germany, Austria, Hungary, and France) and manufacture vehicles for various premium brands. They cover a wide range of different products from compact models to roadsters and luxury sedans. Data collection took place over several years in the course of various industrial projects, where problem-centered interviews with experts from the companies were performed. For confidentiality reasons, the study only conveys information which is publically accessible, e.g. by plant tours which are offered to customers or other visitors. This approach is also meant to make replication studies easier and thus increase the contribution to scientific research.

As this paper is not interested in any specific company strategy, data analysis focused on general characteristics of the sequencing and scheduling tasks in the factories and the specific types of requirements which are taken into consideration during the search for solutions. The findings are aggregated to a general description of the problem situation, following the notation introduced in the previous chapter for the permutation flow shop problem. It accordingly discusses (1) the job list resulting from the production orders, (2) the machines, plants and factory layouts, and (3) the cost function used to evaluate solution quality.

Although specificities of the various factories and manufacturing logics of the companies are addressed, the result does neither claim to give an accurate account of any single facility, nor to exhaust all the aspects of interest for the companies which were involved. The model presented here is instead meant to provide the vignette of a typical problem formulation which can serve as a basis for the design of an appropriate solution procedure.

## 4. Findings

### *4.1. Orders and job lists*

The job list contains the order information for every single vehicle to be manufactured. The order information consists of different kind of data, starting with a unique code which will be engraved in the body to identify the vehicle through its whole lifecycle. Once the number is engraved, the configuration of the vehicle cannot be changed any more, apart from minor equipment options. The code corresponds to a certain model series, body type and destination. Since different countries have different regulations for the design and equipment of vehicles, the destination determines various of their attributes, including the position of the steering wheel, the lights, airbags and other safety features, engines and exhaust cleaning devices etc. This information is also included in other data connected to the order, such as the model series, model year and option codes.

Table 1 illustrates order variety in manufacturing based on the available customization options in sales. No data was made available about the extent to which customers make use of this variety and its fluctuation over time. In any case, however, manufacturing should be prepared to process all potential customization. The figures for the compact model indicate the lower bound of variety, as this is one of the most economic vehicles produced in the factories. The figures for the mid-sized sedan show that the variety is considerably higher for other models. Since many factories produce different models on the same lines, the number of different configurations can easily surpass several billions.

Table 1. Examples for order variety in different dimensions

| Dimension | Compact Model | Mid-Size Sedan |
|---|---|---|
| Engine/ Transmission | 6 | 13 |
| Exterior/ Wheels | 8 | 32 |
| Colors | 12 | 14 |
| Interior/ Upholstery | 3 | 27 |
| Option Packages | 15 | 24 |
| Further individual Options | 8 | 63 |
| Overall variety | 207,360 | 237,758,976 |

Another important order attribute is the due date of the vehicle, which can either express the completion of production or the delivery to the customer. With information about the destination and the shipment times, the delivery date can be derived from the production date and vice versa.

Manufacturing also considers order information which is not conveyed to the customer, for example additional details on updated equipment versions, in particular when they have implications for other parts of the vehicle, too. While this information is mostly calculated after the order is scheduled for production, it is in some cases necessary to plan it in advance from the incoming order data.

All companies included in the study have spent considerable effort to reduce variety in the body shop. Nevertheless, there are still many different body versions which have to be distinguished because of different models which are produced on the same line. The technical design of the vehicles can also have implications for the body, for example because of the positions of different types of engines, transmissions, and the steering wheel, sun roofs, exhaust systems, special seats and heating systems or other attributes. Variety in the body shop has a positive effect on the weight of the vehicles, because all unnecessary parts can be omitted.

### 4.2. Machines, operations and plant layouts

Problem instances in practice consider not only physical installations in the factory as machines, but also all other recurring procedures causing effort in manufacturing. This includes double paint jobs for certain orders or quality controls and delivery processes after a vehicle is produced which require an earlier production of the vehicle to meet the due date. Some factories, for example, consider the times at which trucks, trains or ships leave to transport volumes of vehicles to certain destinations to ensure that vehicles with similar destinations can be shipped together soon after production.

For each machine $M_j$, an operation $O_{MjJi}$ can be defined which relates specifically to a job $J_i$. However, the production logic also requires the consideration of additional operations at the machines which depend on the order of the jobs in the sequence, such as cleaning procedures after color changes in the paint shop or shipment activities after completion. This information has to be made available in the model for the evaluation of the sequence.

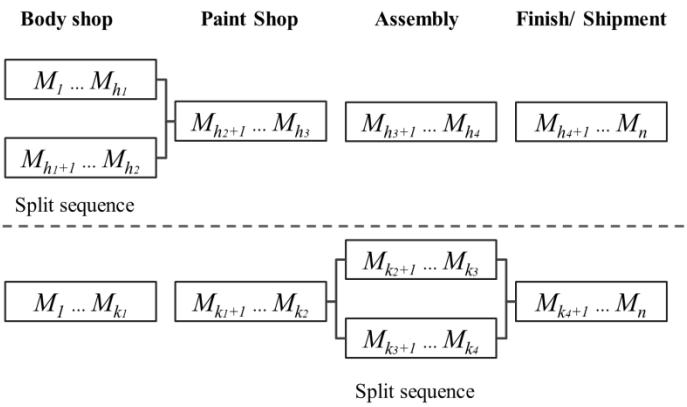


Fig. 2. Examples for different plant layouts

Plant layouts can include different forms of parallel production in the various plant areas (see Fig. 2). Parallel production is particularly important in automatized body shops, where one can often find robots welding together bodies at different stations in parallel (one for sedans, one for convertibles, or other distinctions). Parallel assembly can also be motivated by different operations on the line (e.g. robots for sun roofs only available at one line). Other reasons for parallel assembly can be the treatment of varying production volumes: it is easier to shut down one line and continue production on the other one at normal speed than letting both lines run at half speed.

Knowing all operation in the factories which affect production times, it is possible to derive all sequences and schedules for manufacturing in the different plant areas from one another. From the perspective of shipment, completely separate production facilities can still be considered to produce one sequence as a common output, as a basis for the scheduling all the prior activities.

### 4.3. Evaluation function

Table 2 gives an overview of different types of criteria which are considered in the factories. These criteria can refer to the position of orders with one or several certain options in the sequence or to the scheduled production dates and times on different lines and in different plant areas.

Table 2. Types of quality criteria considered in factories

| # | Criterion | Application Example |
|---|---|---|
| 1 | Min. distance in sequence | Allow mounting times for special options |
| 2 | Max. distance in sequence | Avoid stockpiling near assembly line |
| 3 | Min./ optimal batch size | Avoid frequent color changes |
| 4 | Even distribution over time | Smooth workload/ energy consumption |
| 5 | Max. sum of workload | Avoid work overhead for workers/ robots |
| 6 | Max. number per interval | Respect production capacities as suppliers |
| 7 | Even Number per interval | Ensure regularity of delivery procedures |
| 8 | Target delivery date | Low storage time, punctual delivery |
| 9 | Batch production finish date | Shipment of vehicles to same destination |

In order to evaluate the criteria, it is first necessary to determine the position of the orders on all the lines they pass in the different plant areas where criteria are defined, and to calculate the according dates and times which affect parts delivery and shipment. This allows the calculation of numbers per shift or day and the fulfillment of specific due dates. Criteria related to the actual sequence are further illustrated by the following figures.

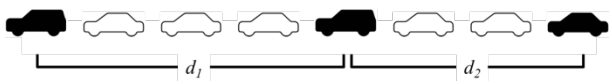


Fig. 3. Illustration of distances in the sequence

Distances are measured by counting the number $k$ out of $n$ consecutive orders across the whole sequence, with $k = 1$ as the most frequently used case (see Fig. 3). Manufacturing may require minimum distances between certain types of orders because of mounting times or benefit from an even distribu-

tion of certain types of orders across the sequence to smooth parts supply.


Fig. 4. Illustration of batches in the sequence

Forming batches of orders with the same equipment options (see Fig. 4) is mainly required for painting and shipment issues. While the paint shop might benefit from a lower number of color switches independently from the exact length *b* of the batch, shipment on trucks requires an exact number of orders with the same destination kept together.

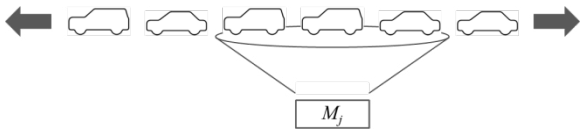


Fig. 5. Illustration of workload per station

Workload issues in manufacturing can concern either the effort to process consecutive orders at one station (Fig. 5) or the effort caused by orders on several consecutive stations (Fig. 6). The former gives account of capacity constraints of machinery installed at the station. The latter is rather related to workers who cover various stations together.

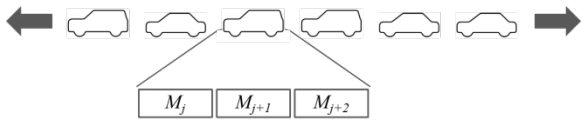


Fig. 6. Illustration of workload on consecutive stations

Factories consider between 30 and 200 criteria of different types. Their aggregation results in a multi-modal evaluation function. Since it is highly unlikely that a perfect solution exists which completely fulfils all criteria at the same time, the construction of the cost function to penalize deviations plays a decisive role. There are numerous different ways how deviations from the target value can be calculated, in particular when positions in the sequence are concerned. For example, it is possible to measure the spread of orders which are supposed to be kept together in one batch, or just the deviation of the batch size. In the same way, there are also different ways how aggregations of cost functions can be calculated. For the factories considered in this study, no common best practice for measuring violations or aggregating the values could be identified.

## 5. Discussion and Outlook

### *5.1. Impact of increased agility*

Agile manufacturing in the automotive industry confronts practitioners in the factory with many different constraints for production sequencing and scheduling. They do not only concern manufacturing issues in the factory, but also external requirements from parts supply, sales and distribution. The criteria which need to be considered in sequencing and scheduling are in consequence plentiful. At the same time, they are also quite diverse and referring to different plant areas with different shift breaks and potential parallel production.

The conceptual approach presented in this paper allows a comprehensive description of this situation by modelling the machines and operations in the factory, the job lists resulting from the order volume, and the evaluation function to assess the effort required in manufacturing of all possible sequences. Two specific challenges resulting from increased agility can be highlighted.

First, the data show that up to 200 different criteria are taken into account in sequencing and scheduling. Highly customizable vehicle orders make it impossible to predict the exact combinations order attributes which appear in the production daily volumes. While it might be possible to control the number of production orders for which each single criterion applies, all the different combinations of criteria on the changing order volumes can hardly be expected to be manageable. Most factories have a production capacity between 1000 and 2000 orders per day, which creates an immensely large solution space in terms of possible production sequences.

Second, different types of criteria reflected in the constraints on the sequences and schedules are hard to set in relation to each other. Given the size of the solution space, possibilities to fulfil different criteria at the same time remain unclear, as well as the form and extent of violations which need to be admitted. Heuristic search for best solutions is in this way just as much an exploration of the potential to optimize sequences and schedules, with the results generated by the algorithms as the only point of reference being available.

### *5.2. Implications for solution techniques*

Solution techniques based on the principles of iterated local search have already received wide attention in the context of the car sequencing problem and many other similar challenges. They are still applicable under conditions of increased agility, which sets them apart from other analytic procedures. It seems necessary, however, to think differently about the role they play in practice.

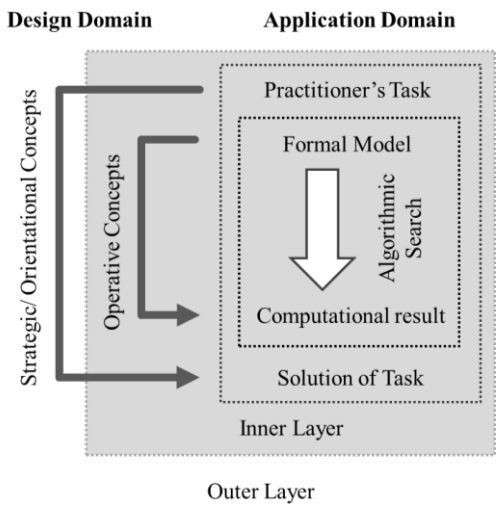


Fig. 7. Principle of iterated search

Drawing on C-K design theory, Fig. 7 describes the task of practitioners concerned with sequencing and scheduling as a double-layered process. In the outer layer, the problem is understood and expressed in formal terms, such that a systematic solution activity can be started, and the result is referred back to the actual working conditions under which it is used. In the inner layer, the solution approach is executed with the help of suitable algorithms.

As a result of increased agility, both layers seem to merge: understanding the problem goes in parallel with solving it, as the insights gained about possible solutions add to the practitioners' understanding of the problem situation. The design of suitable algorithms therefore needs to be reflected from an operative perspective, but as well from a more strategic, orientational perspective, in terms of the added value for understanding the problem situation at hand.

## 6. Conclusion

Agile manufacturing strategies in the automotive industry have created new challenges for sequencing and scheduling orders for production in the factories. These challenges are caused by the shift towards customer orientation which has taken place during the last decades among all manufacturers. This shift has increased the complexity of products and manufacturing processes and created the need to consider a larger variety of constraints. Prior research has investigated instances of sequencing and scheduling problems in detail, but is has given little attention to the effects of continuously changing order volumes and the full diversity of different criteria which are used in practice.

In order to fill this gap in literature, this paper presents empirical evidence from various factories in Central Europe about order variety, plant layouts and quality criteria which are used in the practice of sequencing and scheduling. Furthermore, it discusses the volatility of the data over time. The findings show that the complexity of the situation is very high. Commonly used problem instances for the design of algorithmic solution techniques only reflect a fraction of it. This does not mean that such solution techniques are not applicable, but it suggests that they have to be reviewed from a different perspective.

Future research is necessary to discuss practical challenges in more detail and move from the general findings presented in this paper to more specific and accurate descriptions of the practitioners' tasks in the factories. On this basis, it will become possible to study how search algorithms can be best adapted to changing order volumes and quality criteria, and how the process of finding solutions is intertwined with the process of gaining a better understanding of the given problem situation among the practitioners who are responsible for sequencing and scheduling in the factories.

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# Data-driven Operations Management: Organizational Implications of the Digital Transformation in Industrial Practice

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## Abstract

The ongoing digital transformation on industry has so far mostly been studied from the perspective of cyber-physical systems solutions as drivers of change. In this paper, we turn the focus to the changes in data management resulting from the introduction of new digital technologies in industry. So far, data processing activities in operations management have usually been organized according to the existing business structures inside and in-between companies. With increasing importance of Big Data in the context of the digital transformation, the opposite will be the case: business structures will evolve based on the potential to develop value streams offered on the basis of new data processing solutions. Based on a review of the extant literature, we identify the general different fields of action for operations management related to data processing. In particular, we explore the impact of Big Data on industrial operations and its organizational implications.

**Keywords:** big data, operations, industry 4.0

Final draft of the manuscript. The version of record has been published and is available in Production Planning & Control, Volume 28 (2017) Issue 16; pp.1332-1343, http://www.tandfonline.com/10.1080/09537287.2017.1375148

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## 1 Introduction

The diffusion of digital technologies has quickly progressed over the past ten years. Data processing applications have permeated practically every field of human activity and reach nowadays far beyond their traditional fields of application into the private lives of their users (Yoo et al. 2012; Fritzsche 2016). By virtue of their ubiquitous presence, digital technologies allow previously unfeasible solution designs which are expected to disrupt existing business structures and create new fields of economic growth (e.g. Lee 2008; Porter and Heppelmann 2014). In the context of industry, this dynamic is frequently addressed as a forth revolution after (1) the introduction of machine-based labour in the 18$^{th}$ century, (2) the moving conveyor belts and job breakdowns of the early 20$^{th}$ century, and (3) the automatization of production in the late 20$^{th}$ century (Lasi et al. 2014; Kagermann et al. 2013). To remain competitive despite all disruptions, companies have to ensure that their business operations are highly flexible and adaptable to economic and technical change (Westkämper 2011).

The digital transformation of industry does not progress with the same speed in all fields of application. Numerous efforts to collect and exploit digital data were undertaken long before the turn of the millennium. Logistics and procurement, for example, have built huge data warehouses and information networks in the 1990ies to gain better insight and control about inventories, production volumes, and shipping processes in huge data warehouses (Stadtler 2015). This enabled companies to engage in new forms of Supply Chain Management (SCM) and Enterprise Resource Planning (ERP), with an enormous impact on the organization of industrial operations and the overall structure of business activity in manufacturing (Gunasekaran and Ngai 2004; Oberniedermaier and Sell-Jander 2002). The achieved performance finds a significant association in the degree of ERP systems integration and restructuring of organisation (Jungbae Roh and Hong 2015). Today, the volume, range and speed of data collection have exponentially grown. A simple extrapolation of the experiences with ERP and SCM allows a first estimation of the future impact of digital technology on industry and society, supporting the view that the ongoing transformation has the potential to dwarf everything that happened in the 20$^{th}$ century, in terms of technological as well as socio-economic change (Lee 2008).

The future impact of the digital transformation, however, cannot be adequately predicted by simple quantitative extrapolations from previous experience with information technology. There are also qualitative differences to consider, caused on the one hand by the further development of systems architectures and hardware elements, and on the other hand by the characteristics of the subject matter (Brettel et al. 2014). Data warehouses and systems applications of the late 20$^{th}$ century were for the most part built as centralized solutions in accordance with the existing structures of operations managements (Mertens and Griese 2002). Current approaches rather favour decentralized technical designs of distributed programming with a high level of autonomy (Bauernhansl et al. 2014). Furthermore, they explore possibilities to capture new value streams in vertical integrations of business activities across institutional boundaries (Kagermann et al. 2013). Collaborative supply networks for

customized production are necessary to address the growing demand for individualized products (Fornasiero et al. 2016). Such value streams are not reflected by the existing organizational structures of industrial activity. In order to gain operative control over these value streams, companies have to introduce radically new managerial concepts which reflect the potential of digital technologies to develop new business opportunities. In this respect, information technology and operations management can be said to have switched roles: the possibilities of data processing take precedence over the organizational structures of industrial activity (Yoo et. al 2010).

Research on digital technologies has already provided a lot of insight into the potential of new solution designs in numerous fields of industrial application (Chen et al. 2016; Oks et al. 2016). So far, however, the organizational implications of these designs for operations management have only been sporadically addressed. An overall picture is still missing. This can be explained by the large variety of operative constraints across the different fields of application. We propose that there is nevertheless one perspective on digital technologies which allows us to draw general conclusions for operations management. This perspective turns the attention to the treatment of data in the different fields of application. What they all have in common is that they produce large volumes of data high velocity and variety. Such data, which are usually described as Big Data, cannot be stored and processed in the same way as data in conventional data warehouses (Bendre and Thool 2016). They need to be treated in a different way. In this paper, we review the extant literature on digital technologies to extract recurring patterns of big data management and analytics. We use our findings to create a structured overview of the challenges of digital technologies for operations management and the consequences which have to be drawn out of it in terms of organizational change.

The paper is divided in 5 chapters. Chapter 1 introduces to topic and motivation. Chapter 2 explains the background of Industry 4.0 and the capabilities of Big Data solutions. Chapter 3 describes the method used to extract data processing requirements from current research publications. Chapter 4 presents and explains results. Chapter 5 closes with discussion of requirements and matching with capabilities of Big Data solutions.

## 2 Background

### *2.1 The digital Transformation of Industry*

In its literal sense, digitization means the encoding of data in digital formats. Data which has previously not been available for digital data processing thus becomes available. Digitization in industry started with data of high granularity with a low update frequency. Today, an increasing number of data is created by permanently operating sensors which measure highly specific attributes of physical processes with as similarly specific functional domain (Lee, 2008). The connection of the data with other digitally encoded data allows the creation of new structures to manage and control these objects. It makes them programmable, addressable,

sensible, communicable, memorable, traceable, and associable (Yoo 2010). Through the association of physical processes with computational events, physical objects and their formal, symbolic representation can be addressed together. As a consequence, systems can be created which, according Geisberger and Broy (2012), "use sensors to capture data about what is going on in the physical world, interpret these data and make them available to network-based services, whilst also using actuators to directly affect processes in the physical world and control the behavior of devices, objects and services. These systems are known as Cyber-Physical Systems (CPS)".

In the course of the ongoing digital transformation of industry, products and production systems like machines, warehouses and operating resources are enhanced to such Cyber-Physical Systems (CPS) and connected to global production networks (Kagermann et al. 2013). The entities are commonly considered to possess a certain, local intelligence which enable them to execute autonomous decision procedures, communicate with each other, interpret available data, and trigger actions. In exchange with others, such entities can also form regulatory cycles with abilities of self-control and self-optimization (Lee, 2008). Intelligent products can be clearly identified, located at all times, know their history, status and alternative ways to completion. Intelligent production systems are connected to company's business processes, IT-systems and to the entire value chain in the production network. This enables real-time control and optimization of the value chain, starting with an order to the final delivery of the product (Kagermann et al. 2013). The convergence of the physical world and the digital world with CPS enables the new paradigm of autonomous and decentralized production (Brettel et al. 2014; Monostori 2014).

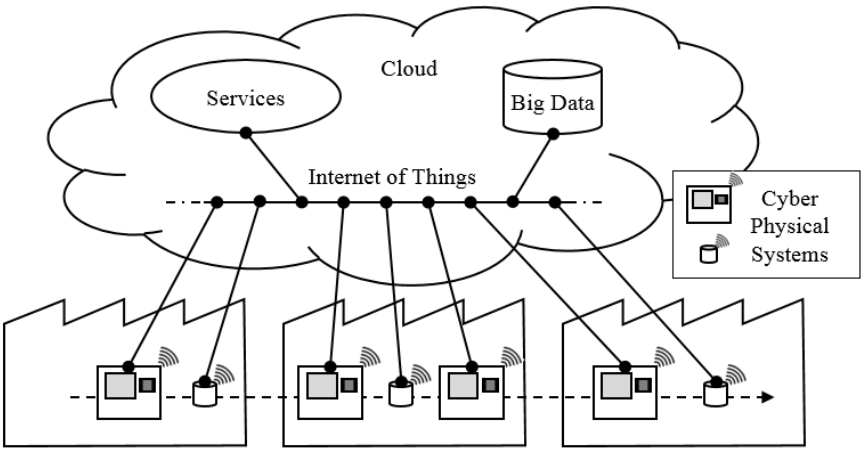


Figure 1. Solution-components of Industry 4.0

In order to highlight the revolutionary potential of the digital transformation of industry, it has become popular to address it by the term "Industry 4.0", which was first publically introduced at a German industry fair in 2010. The current discourse on Industry 4.0 names a wide manifold of concepts and solution-components (Figure 1). This includes, but is not limited to (1) CPS as intelligent entities in production (Sztipanovits et al. 2013), (2) Internet of Things

as communication platform for CPS (Madisetti and Bahga 2014), (3) Cloud solutions for decentralized services (Verl et al. 2013) and (4) Big Data solutions for high-performance processing of large data amounts in production (Kagermann et al. 2013; Lee et al. 2013). The diversity of Industry 4.0 solution designs is mainly driven by the almost endless variety of purposes for which CPS can be applied. This includes self-organization in manufacturing and logistics, self-maintenance and repair, improved safety and robustness, real-time control, and more (Monostori 2014). Further diversity is caused by the specific requirements of the different subject matter in manufacturing, energy, mobility, health, and private consumption (Rehm et al. 2015). In terms of data management, on the other hand, the solutions which are discussed show many similarities which allow us to draw general conclusions about the implications of the digital transformation of industry for operations management.

### *2.2 Big Data Applications*

The exponentially increasing amount of data used by digital technology has further consequences for application design. Previous information systems architectures considered data as a passive resource which could originated somewhere and was then extracted, transformed and related to other data according to a predefined data model. During the last years, the attention has shifted instead to more dynamic forms of data processing without reference to any predefined structural model. Data are increasingly considered as so-called Big Data. Drawing on early discussions among practitioners and consultants, Big Data are commonly characterized by the 3 V's: large volume, variety and velocity (Chen et al. 2014). Big data require further processing after collection in order to determine their relevance and interrelatedness, using algorithmic techniques such as association rule learning, cluster analysis, ensemble or machine learning, natural language processing, pattern recognition, spatial analysis and many more (Chen et al. 2016; de Mauro et al. 2015). The significance of the data for application consequently does not only depend on their origin, but also on the design of the methods used for their further treatment. For this reason, various authors have added further terms to the 3V's, such as value for application and veracity (Dijks 2012; Schroeck 2012). The design of the information systems used for processing the data can thus not be considered as independent from the exploitation of the data in business contexts (see also Fritzsche 2009). This turns Big Data into an important topic for the organization of operations management activities.

In comparison to CPS, research on Big Data is more closely connected to operative systems than prototypes and pilot applications. This makes it possible to discuss Big Data in reference to different software solutions rather than general application scenarios. Apache Hadoop is one of the most wellknown Big Data software solution, however, there is a great variety of others solutions e. g. Redis, SimpleDB, CouchDB, MongoDB, Terrastore, HBase or Cassandra (Cattell 2011). A common technical criterion to determine the scope of Big Data is the usage of NoSQL data bases. Several taxonomies have been proposed to classify the different NoSQL data bases (Cattell 2011; Pokorny 2013). Pokorny (2013) for instance uses the criteria of the data model and identified three kind of models: Column-oriented (e. g.

Cassandra), key-value (e. g. SimpleDB) and document-based (e.g. Mongo DB). Another criterion is related to principles of data processing (Agrawal et al. 2011). The first principle is batch processing and distributed computing of data (Gupta et al. 2012). Large and complex data is split into small subsets and then processed concurrently. A common algorithm is MapReduce which is tuned for a specific use cases. A representative software solution for this principle is Hadoop HDFS with MapReduce (White 2012). The second principle is to store data in a semi-structured data model which is adapted to the specific access pattern of a use case (Kaur and Rani, 2013). This enables real-time queries and random access on data without time-consuming operations and data joins. The software solutions Cassandra (Hewitt 2010), SimpleDB (Chaganti and Helms 2010) or MongoDB (Chodorow 2013) are representatives of this principle.

Both classification criteria (data model, principles of processing) are important characteristics when selecting a proper solution design for a specific use case. Table 1 compares four different designs regarding general capabilities and characteristics. Each design is a representative for the classification described above. A final selection of an appropriate Big Data software solution depends on use case, existing infrastructure and application scenario.

Table 1. Capabilities and characteristics of representative Big Data software solutions

| BIG DATA SOFTWARE SOLUTIONS | | | | |
|---|---|---|---|---|
| Capabilities /Characteristics | Hadoop HDFS & MapReduce | Cassandra | MongoDB | SimpleDB |
| Data model | File system | Column | Document | Key-Value |
| Batch processing / distributed computing | Yes | No | No | No |
| Real-time queries | No | Yes | Yes | Yes |
| Random access | No | Yes | Yes | Yes |
| Horizontal scaling | Yes | Yes | Yes | Yes |
| Strength | Data processing | Write | Read | Full Indexing |
| Architecture type | Master-Slave | Peer-to-Peer | Master-Slave | Web Service / Cloud Computing |
| CAP theorem | Consistency, Partition Tolerance | Availability, Partition Tolerance | Consistency, Partition Tolerance | Availability, Partition Tolerance |

## 3 Research Design

Our research interest in this paper is directed at the implications of the digital transformation of industry for operations management. We propose that such implications can be derived from the study of Big Data management in the context of new digital technologies. For this reason, we review the extant literature in the field to identify common patterns in the treatment of Big Data which need to be considered from an operations management perspective. Our findings are then used to draft an overall picture of the data-oriented operations in industry which can serve as a basis for a re-organisation of operations management.

A widely accepted method in IS research to make valid interference from text can be found in the scientific technique of content analysis (Myers 1997). Content analysis uses clear rules and systematic procedures for analysis and interpretation of text (Klenke 2008; Krippendorff 2004; Mayring 2000). Compliance of rules and procedures delivers rigorous and replicable results (Krippendorff 2004). Core of the content analysis is a category scheme, achieving the objectives of analysis. Categories can be developed by deduction from theory or by induction using the analysed material (Mayring 2000). As relevant theory in the field of new digital technologies is widespread in various scientific disciplines (including production, logistic, IT, AI, mathematics, and more), this study uses an inductive category development approach based on scientific publications in related to the digital transformation of industry. This allows a grounded interpretation of material without pre-assumptions.

The process of content analysis:

The analysis of requirements of new digital technologies in industry regarding data processing was conducted using the process of content analysis according to Mayring (2000, 2008). Our object of analysis was the vision, objectives and concepts expressed in extant scientific literature in the field. The analysis was conducted with the objective to create a structured compilation of explicit and implicit requirements for data processing in the Industry 4.0 concept. More specifically, the analysis was guided by the following two research questions: (1) What are the requirements regarding the data that need to be processed? (2) What are the requirements regarding the processing of the data?

The search was conducted on journal papers, conference papers and white papers from the following scientific sources: general databases (ScienceDirect, IEEE Explore, Google Scholar), German journal data bases (ZWF, WT, IM). Publications were filtered using the keywords ‘industry 4.0’, ‘cyber physical system’, ‘internet of things’, ‘autonomy’, ‘decentralized’, ‘self-control’ in combination with the keyword ‘production’, ‘manufacturing’ or ‘logistic’. The filter was applied on title, abstract and keywords of publications in the period 2005 to 2015. The search resulted in 117 publications.

After selection of the material, rules for the process of category development were defined. Therefore, unit of analysis, selection criteria and level of abstraction were specified. The unit of analysis defines rules for the amount of text which is the basis for interpretation. As requirements are mostly described in implicit form, we choose ‘phrase’ as minimum and ‘section’ as maximum unit of analysis. This allows understanding and interpretation of requirements in the individual context of the paper, expressed in short statements as well as larger arguments. The selection criteria defines decision rules whether a unit of analysis contributes to the research question and objectives of analysis. In case of data processing, we analysed requirements regarding (1) Data: types, structure, format and sources and (2) Processing of data: operations, performance and conditions. The level of abstraction defines the rules to build a category for a unit of analysis which fulfils the selection criteria. In case of data processing requirements of industry 4.0, the rule is to choose the level of abstract in a

way that categories for requirements are not specific to any approach or solution, but are applicable to the context of the digital transformation of industry in general.

As a next step, one researcher reviewed parts of the material applying the defined rules. The review was conducted using the software MAXQDA. The categories derived in this first loop were built closely from material. After only a few new categories occurred, a revision of rules and category scheme was conducted. Categories were merged to related aspects to receive distinct categories. Each content of the 27 resulting categories was then checked for reliability and its fit in the category, by means of a category description. Based on the resulting categories and codes the final examination of the material was conducted. A summative check of reliability was performed upon the coding of a second researcher. Therefore, the second researcher was instructed in object, objectives, research question and rules and then analyzed parts of the material. Mayring (2008) proposes a reliability of at least 70% for acceptable results of a content analysis. The summative reliability was calculated according to Holsti (1969) and proves the reliability of this analysis. Table 2 shows the aggregated reliabilities for each main category.

Table 2. Number of codings and summative reliability by main category

| Category | C10 | C20 | C30 | C40 | C50 | C60 | C70 | Total |
|---|---|---|---|---|---|---|---|---|
| Codings of Coder 1 | 27 | 34 | 23 | 73 | 27 | 29 | 20 | 233 |
| Codings of Coder 2 | 25 | 30 | 28 | 81 | 30 | 27 | 18 | 239 |
| Matching Codings | 22 | 26 | 19 | 54 | 24 | 22 | 15 | 182 |
| Summative Reliability | 85% | 81% | 75% | 70% | 84% | 79% | 79% | 77% |

## 4 Findings

The result of our analysis is a structured compilation of requirements regarding data processing. It provides a comprehensive view on the content types that need to be processed and on the processing of that data in a digitalized environment. This result could only be produced by the accumulation of the findings, as the vast majority of the publications only addressed certain aspects or solution-components, without describing general requirements or structures for requirements. Table 3 shows the resulting category scheme with 6 main categories and 27 subcategories describing object, subject and conditions of data processing. According to our two research questions, it is grouped in requirements for data and for processing of data.

The first main category ‘Data Model’ (C10) shows requirements for characteristics of data, structure and sources to integrate in the context of the digital transformation of industry. The subcategory ‘Unify semantics’ contains requirements for a unified description of information and meanings in production. The unification of interfaces between entities in production are content of the next subcategory ‘Unify interfaces’. Together, semantics and interfaces address communication and data exchange among CPS in a comprehensive production network which

various systems and objects. The second main category ‘Data Integration’ (C20) refers to different perspectives of data integration within an enterprise and beyond. The first subcategory ‘Integrate life cycle’ contains requirements to integrate life cycle data of CPS in engineering and operation processes. The next subcategory ‘Integrate horizontally’ focuses on requirements to integrate data along the value chain in an entire production network. The third subcategory ‘Integrate vertically’ contains requirements to integrate data from the automation pyramid (enterprise-, control-, device- and sensor-level). The third main category ‘Data content’ (C30) shows requirements for necessary data to be processed. Necessary data comprises authorization, specification, capabilities, production data, business data, condition data, sensor data, order data and knowledge.

The fourth main category ‘Decision processing’ (C40) refers to requirements for autonomous, de-centralized self-control and self-optimization performed in CPS networks. The first subcategory ‘Monitor conditions’ includes requirements for a permanent monitoring of conditions and health of production processes and equipment. Requirements for triggering decision-making depending on current situation are dedicated to subcategory ‘Ad-hoc reaction’. The subcategory ‘Admit autonomy’ contains requirements for autonomy and freedom in decision processes in CPS networks. The next subcategory ‘Optimize network’ focuses on requirements for overall system goals and optimization when local decisions are made by CPS. Requirements for utilization of comprehensive models of the current production are part of the subcategory ‘Utilize models’. The fifth main category ‘Knowledge processing’ (C50) refers to requirements for processing of actual and past data to generate knowledge and additional value for decision-making. The subcategory ‘Generate models’ contains requirements to derive models and rules from knowledge, generated from historical data in production. Requirements to adapt knowledge, models and data depending on application context are part of the sub-category ‘Adapt knowledge’. The next subcategory ‘Transform know-how’ contains requirements to transform expert knowledge and experience in information models. The sixth main category ‘Real-time processing’ (C60) focuses on requirements for processing performance. Requirements to access entities and data in real-time are part of the subcategory ‘Real-time data access’. The next subcategory ‘Real-time communication’ contains requirements for real-time communication and data exchange among CPS and within a network. Real-time requirements for operative production control are part of the sub-category ‘Real-time control’. The last main category ‘Safety and protection’ contains requirements for IT-security within overarching value networks. The subcategory ‘Network safety’ refers to requirements to identify entities as prerequisite for communication and data exchange. The last subcategory ‘Data safety’ focuses on roles and rights for all entities to control data access and communication.

Table 3. Resulting Categories for data processing requirements of Industry 4.0.

| DATA REQUIREMENTS | | |
|---|---|---|
| **Main category** | **Subcategory** | **Requirement Description** |
| Data model (C10) | Unify semantics (C11) | Unify information models an meanings |
| | Unify interfaces (C12) | Unify interfaces and communication |
| Data integration (C20) | Integrate life cycle (C21) | Integrate data along the life cycle of CPS |
| | Integrate horizontally (C22) | Integrate data along the value chain and network |
| | Integrate vertically (C23) | Integrate data of automation pyramid |
| Data content (C30) | Include authorization (C31) | Include identification and access rights of CPS |
| | Include specification (C32) | Include technical specification of CPS |
| | Include capabilities (C33) | Include capabilities and properties of CPS |
| | Include production data (C34) | Include work plan and instruction of CPS |
| | Include business data (C35) | Include business data and parameters of CPS |
| | Include condition data (C36) | Include condition and status data form CPS |
| | Include sensor data (C37) | Include sensor an actor data from production |
| | Include order data (C38) | Include customer data and conditions of delivery |
| | Include knowledge (C39) | Include knowledge from analytics |
| **PROCESSING REQUIREMENTS** | | |
| **Main category** | **Subcategory** | **Requirement Description** |
| Decision processing (C40) | Monitor conditions (C41) | Monitor conditions of actual production processes |
| | Ad-hoc reaction (C42) | Control processes depending on situation |
| | Admit autonomy (C43) | Admit autonomy in decision-making of CPS |
| | Optimize network (C44) | Optimize network in local decision-making |
| | Utilize models (C45) | Utilize comprehensive models of real production |
| Knowledge processing (C50) | Generate models (C51) | Generate models and rules from knowledge |
| | Adapt knowledge (C52) | Adapt knowledge to conditions of decision |
| | Transform know-how (C53) | Transform know-how and expert knowledge |
| Real-time processing (C60) | Real-time data access (C61) | Access data and CPS in real-time |
| | Real-time communication (C62) | Communication und data exchange in real-time |
| | Real-time control (C63) | Control and coordination of processes in real-time |
| Safety and protection (C70) | Network safety (C71) | Protect network against unauthorized access |
| | Data safety (C72) | Protect data against unauthorized access |

## 5 Discussion

### *5.1 Data processing Requirements of new digital Technologies*

Our findings suggest that the digital transformation of industry shifts the attention in the search for improvements of efficiency and effectiveness from physical production processes to the management of data involved in it.

Such improvements require a comprehensive integration of data (C20) and standardized semantics and interfaces (C10) to enable efficient communication and data exchange (Atmosudiro et al. 2014; Klocke et al. 2013). Activities for data integration include the horizontal, vertical and life cycle perspective (Brettel et al. 2014; Vogel-Heuser et al. 2009). Regarding the data content (C30), results show a wide range of data, covering the whole life cycle of a cyber-physical system in Industry 4.0. Besides specification (C32), the description of capabilities (C33) of cyber-physical systems is required to enable self-aware entities and self-organizing operational processes (Denkena et al. 2013; Höme et al. 2015; Letmathe et al. 2013). Furthermore, business data (C35) is required for monetary evaluations in operational decision-making (Fleischer et al. 2013; Lanza et al. 2013; Rekersbrink et al. 2007). This requirement was already part of the CIM-concept and finds it´s revival in Industry 4.0 (Mertens 2014). The comprehensive usage of knowledge (C39) from historical data in form of models and rules is another characteristic of Industry 4.0 (Auerbach et al. 2013; Frazzon et al. 2013).

Efficient processing of comprehensive data is another requirement of Industry 4.0. Entities like machines perform continuous monitoring of their own conditions and of their environment (C41) to detect critical deviations or situations (Herkommer and Hieble 2014; Lee et al. 2014) and to perform ad-hoc reactions (C42) upon critical situations (Grundstein et al. 2013; Overmeyer et al. 2013). Decision processes target the optimization of overall value chains or rather overall production networks (C44) (Rekersbrink et al. 2007), even when decisions are made by autonomous, decentralized entities (C43) (Blunck and Windt 2013; Rehder and Schatz 2014). Further enhancement of decision process in Industry 4.0 require the usage of a wide range of extracted and formalized knowledge (C50) generated from historical data (Auerbach et al. 2013; Lee et al. 2014). This knowledge can be used to determine parameters or predictions for decision processes. Sensors in the operative production deliver data in cycles of milliseconds (C37) (Bauernhansl et al. 2014). As a result, there is a huge and continuously growing amount of historical data which need to be processed. The requirement for real time processing (C60) addresses the access of entities and their data within the network (C61) (Plorin et al. 2013; Reinhart, Engelhardt, and Geiger 2013) as well as communication and data exchange among entities (C62) (Jatzkowski and Kleinjohann 2014; Scheifele et al. 2014) and real-time control (C63) (Sztipanovits et al. 2013). All interaction and communication among entities require processes for identification and application of rules and roles for data protection and security (C70) (Holtewert et al. 2013; Franke, Merhof, and Fischer 2010).

### *5.2 Implications for Operations Management*

Figure 2 gives an overview of the new dynamics of data management which have to be considered by operations research in a digitalized industrial scenario. They can be organized in four different domains: a) adapted decision processes, b) extended repertoire of data, c) expanded data management, and d) big data treatment.

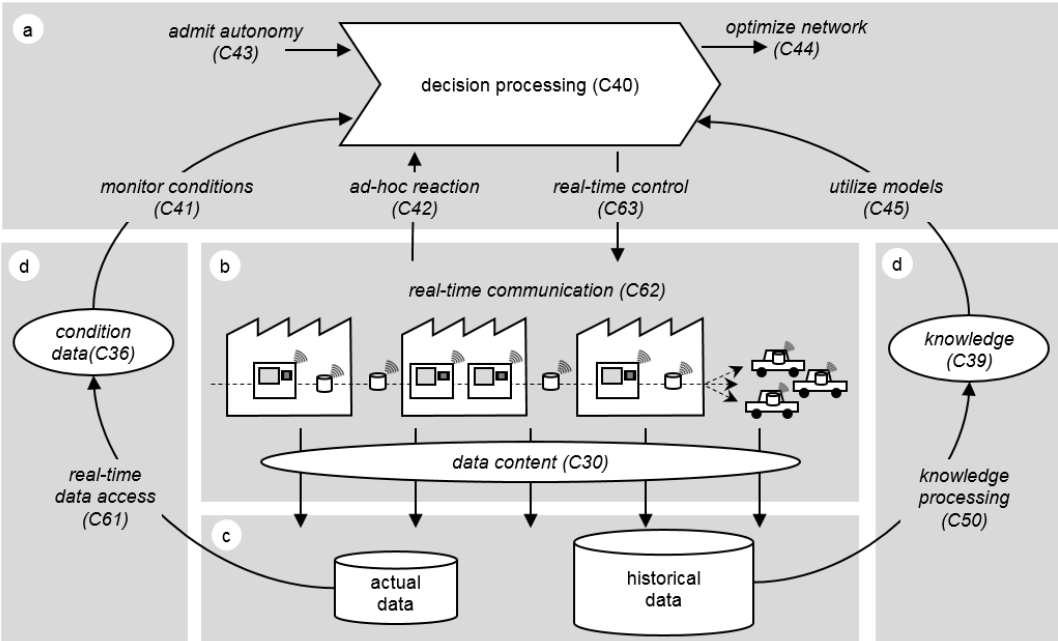


Figure 2. Levers of data-driven decision-making in operations

a) Adapted decision processes

Because of the changing quality of the data that are processed, operations management needs to revise the logic in which decisions are made. Data give direct insight into the actual state of resources and the progress of value creation processes in the industrial environment (C41). Operations management can react to events on the shop floor and elsewhere in the value creation network without any significant delays (C42). This allows close feedback-loops between decision making and monitoring of its consequences. Decision procedures can optimally be adapted to the present conditions in the value creation network (C63). Decisions can be based on comprehensive models developed from historical data and make use of knowledge about recurring patterns (C45). Furthermore, the decision processes can be distributed across different agents without constant references to a central controlling entity (C43) and situative assessments during the decision processes can reflect the overall requirements of the whole network in a better way (C44).

b) Extended repertoire of data

A lot of the data relevant in digital environments are already taken into consideration by existing approaches to operations management, such as quality data, material characteristics,

product structures etc. in specifications of CPS (C32) as well as manufacturing data like work plans, bills of material etc. (C34); the same applies for status information (C36) regarding logistics and manufacturing in MES and ERP systems (see Sendler 2009; Loos 1999; Mertens and Griese 2002). At the same time, however, new kinds of data become relevant as well. This includes authorization data (C31) as well as machine capabilities (C33). Furthermore, sensorial data which were previously only sporadically retrieved are now available ubiquitously (C37). This creates a comprehensive view of the whole value creation network in large detail (Atmosudiro et al. 2014; Koch et al. 2014). At the same time, a lot of practical knowledge which was so far only accessible as implicit knowledge of engineers, technicians and workers can now be made available in information systems (C39).

c) Expanded data management

The extended repertoire of data goes along with new requirements for data management. Data structures have to be expanded, adapted in related in new ways to give an appropriate account of the actual operations (C31, C33, C39). Furthermore, data which have so far often been kept in separate databases related to specific applications (e.g. CAD, ERP) now need to be accessible via an individual information model, containing all life cycle of entity. This creates further requirements for coordinated updates and consistency checks. Relying on specific interfaces and exchange protocols creates huge risks of deviating information. Therefore, other, more comprehensive solutions need to be introduced (see e.g. Vogel-Heuser et al. 2009). In sum, this can be described as a vertical as well as horizontal integration across whole value creation networks (Anderl et al. 2014; Kagermann et al. 2013), as a comprehensive digital image (or “digital shadow”) of the industrial operations (VDI/VDE 2015). The creation of such an image can be accomplished on the basis of a systematically developed general information model (Höme et al. 2015). Such a model has to consider all specific types of data that are involved (C31-C37).

d) Big data treatment

Last but not least, the specific characteristics of Big Data need to be taken into account. In order to cope with the high volume, velocity and variety of the data, operations management has to adopt new strategies for data treatment which go beyond the systematic routines of loading, transforming and presenting data for further usage in conventional data warehouses. We see three issues requiring high performance processing of large data volumes and appropriate Big Data approaches:

(1) *Instantiation and lifecycle approach of Entities*: Life cycle integration (C21) of entities (e. g. machines) require the instantiation of an object in the information model. All data (C30), active data as well as historical data, have to be stored to be accessible for data processing (e. g. Data Mining). The anticipated growth of objects and of containing data (e. g. sensor data) are drivers for Big Data.

*(2) Knowledge processing of historical data:* Data basis for generating knowledge (C50), are historical data from operational processes (e. g. sensor data, good movement, manufacturing processes). Data mining methods are used to recognize pattern, relations and trends in historical data, to derive rules and models (C51) which can be applied to improve and optimize operational processes (C45). To recognize relations and pattern within historical data requires massive parallel processing of Big Data.

(3) *Real-time access on entities in the network*: Real-time decision-making and control are major requirements for a timely response on operations dynamics (e. g. machine failure, delivery delay) (C60). Actual operation data from the value chain (C41) is required to achieve overall system goals and optimization (C44). This involves random access on data of all entities within an overall network, in real-time (C61).

Comparing these three issues with the capabilities of Big Data solutions (Table 1) leads to the finding, that two unique Big Data approaches are necessary. The issues form two general Big Data use cases with fundamental differences regarding access and processing patterns and underlying data. The first general use case *Knowledge Processing* handles time consuming data analytics, mining and prognosis on large amounts of passive data (C50). Real-time queries and random access on data are not crucial in this case. This requires Big Data solutions that support batch processing and distributed computing e.g. Hadoop HDFS with MapReduce. The second general use case *Entity Access* performs ad-hoc queries on entity data from the overall network for operative decision-making (C40, C60). This requires Big Data solutions that support real time queries and random access. Depending on infrastructure and application scenario Cassandra, MongoDB or SimpleDB could be a relevant software solution. Both use cases have a general character and require individual adaption to the context of application.

## 6 Conclusion

The digital transformation of industry is under way, but it is still far from being finished. Its revolutionary potential, as it is addressed by terms like “Industry 4.0” has not yet fully materialized. As a consequence, the extant literature can only roughly anticipate the future impact of digital technologies, based on general conceptual considerations and first practical experience with prototypes and pilot projects. A literature review like the one performed in this paper reflects all the limitations of its source material. It is constrained by the current state of discussion in the field, and there is good reason to believe that a lot of new insights will be gained very soon which will allow us to draw a much better picture of the digital transformation in the future.

It is also necessary to keep in mind that the nomenclature in research is also still in its early stages. The selection of papers based on specific search terms can therefore easily lead to the exclusion of contributions which are highly relevant to the subject matter, but use a different terminology. This must be considered as a general problem of emerging fields of research

where discourse has not yet progressed far enough to establish a stable vocabulary. We are confident, however, that the consideration of seminal papers like Lee (2008) or Kagermann et al. (2013) in the choice of the keywords has allowed us to reduce oversights of relevant literature to a minimum. Comparisons to other reviews in the field such as Monostori (2014) or Oks et al. (2017) also show that other authors operate with the same vocabulary as we do, which further reassures the robustness of our approach.

Additional limitations are caused by the method of content analysis itself. The method uses a set of rules to analyse text passages. In case of data processing requirements, the context of a statement or of an argument is highly relevant for understanding and interpretation. That´s why we choose ‘phrase’ as minimum and ‘section’ as maximum unit of analysis. However further reaching interpretations of a paper, are not covered by our analysis and might result in additional categories for data processing requirements in the Industry 4.0 concept. Furthermore, our calculation of reliability neglects effects of aggregation and category number (c.f. Holsti 1969). Sources in other languages than German and English have been omitted in disregard of the numerous excellent publications in the field of engineering in French, Chinese and other idioms.

Nevertheless, we believe that our research provides important insights for academia and industry. To our knowledge, we are the first who have studied the implications of the digital transformation for operations management from a data processing perspective. This perspective has allowed us to identify a general dynamic in all the various fields of application of new digital technologies. New ways of processing large volumes of data with a high velocity and variety in the context of Big Data go hand in hand with the introduction of cyber-physical systems in industry. With Big Data, data treatment becomes an integral part of the different activities necessary to arrange and control industrial activity, and as such a major success factor for operations management. Based on our literature review, we were able to identify four domains in which Big Data will affect operations management in the future. Since these four domains span across the conventional organizational boundaries in industry, restructuring efforts are necessary in order to ensure that the revolutionary potential of the digital transformation can be exploited. Companies which successfully undertake these efforts can be expected to gain a huge competitive advantage.

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# Enabling the Democratization of Innovation with Smart Toolkits

*Completed Research Paper*

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## Abstract

*Toolkits for user innovation and design democratize innovation by offering users a solution space to develop solutions that meet their diverse needs. Advancements in manufacturing and IS have given users space for creativity and innovation and the danger of overloading users with too many design decisions, especially when they also have unknown implicit needs. This design science study presents a toolkit that generates and recommends complete solutions to users. It identifies users' implicit needs with a critiquing technique, where users iteratively evaluate recommendations by visually inspecting and selecting matching solutions. It presents artifacts that make up the toolkit and its evaluation by comparing it with a traditional toolkit. The smart toolkit further expands innovation capabilities to society by learning the needs of non-expert users and enabling them with completed solutions instead of the traditional toolkit approach, where users follow a slower, manual, learning-by-doing search process through the needs and solution space.*

**Keywords:** Non-expert users, user innovation toolkits, design science, recommender systems

## Introduction

The increasing permeation of society with digital technologies has created large new solution spaces for innovation, which are widely expected to change the organization of business profoundly (Yoo et al. 2012). Most importantly, it has changed the relationship between technology providers and users by giving the users access to the core activity in the engineer's domain: the design and implementation of new solutions (Fritzsche 2017). Users who have so far been passive consumers are increasingly becoming 'prosumers' (Ritzer and Jurgenson 2010). They provide significant contributions to research and development of solutions (Zhao et al. 2009), add to collective intelligence (Wegener and Leimeister 2012) and provide valuable insights from often under-explored 'sticky' need information (Baldwin and von Hippel 2011). Information technology supports the user integration in innovation activities by various kinds of instruments, including online forums, marketplaces, design toolkits along with digital fabrication technologies like 3d-printing (Moeslein and Fritzsche 2017). Design toolkits and digital fabrication technologies are particularly interesting in this context, as they give the users further independence from large industrial structures and allow them to build at least prototypical solutions on their own (Naik et al. 2016). The resulting increase in user contribution to innovation activities and the resulting societal transformation has been described as the democratization of innovation (von Hippel 2009).

Toolkits for user innovation and design are defined as modular systems for users to innovate and design completed solutions based on their needs, by performing learning cycles of trial-and-error (Franke and Schreier 2002; von Hippel 2001). They are often information systems that enable users to design solutions for their unmet needs within a large solution space. The solution space defines the limits within which users can design with the flexibility of the underlying production processes (von Hippel and Katz 2002). It needs to be sufficiently large to meet diverse user needs (Salvador et al. 2009). The solution space offered by a toolkit can lead to innovation, by enabling the development of new solution information through iterative design steps or customization, by enabling the user to select an existing solution closest to their needs (Naik et al. 2016).

Along with meeting diverse needs, a sufficiently large solution space allows users to enjoy the process of self-design and develop feelings of ownership of the product design (Franke et al. 2010). However, a large solution space has the danger of overloading users, in the form of too many design steps and design options. A large number of potential product configurations itself can lead to also a mass-confusion effect (Huffman and Kahn 1998; Teresko 1994), resulting in a product variety paradox. The paradox states that an increasing number of options to choose from does not lead to better choices by customers, but rather the opposite (Salvador and Forza 2004). Hence, while variety and design flexibility can lead to closer matching with user needs and provides value to users (Franke and Piller 2004), it can also overwhelm them in their decision-making.

The overloading of users can be worse when users do not explicitly know their needs but have implicit needs instead. These implicit needs become explicit as users undergo learning-by-doing cycles of using the toolkit (von Hippel and von Krogh 2013). It is often assumed that users get familiar with the toolkit's solution space, have well-defined needs, an outlined design process and they can break down the design process into steps required to design their products. However, user needs are often not inherent but constructed through interactions (Slovic 1995). These requirements are built through the design process, influenced by their incomplete perception of their environment (Bettman et al. 1998). In toolkits that are beyond simple configurators, familiarizing with the solution space will require them to be very involved with the toolkit and get familiar with what they exactly need along with its design question and options. While initially intriguing, this process can quickly become frustrating, with each learning cycle taking time and effort.

Toolkits that provide users with "focused navigation," i.e., equip users to arrive quickly at matching solutions have been suggested for configurators as a way to reduce the product variety paradox (Trentin et al. 2013) and can also be extended to equip users when designing with an innovation toolkit. However, providing focused navigation is a challenge because of unstable requirements and constraints based on ill-defined environmental contexts. It would also require complex interactions, critically dependent on human cognitive abilities to produce effective solutions. These characteristics of the challenge qualify it to be a wicked problem (Rittel and Webber 1984) and an ideal candidate to be solved by designing artifacts (Hevner et al. 2004; Peffers and Tuunanen 2007). This study hence addresses the research question:

*How can a toolkit enable non-expert users to search through the solution space and find solutions to match their needs?*

The objectives of the study are to design, implement, and evaluate a toolkit prototype that provides focused navigation to non-expert users while addressing both their explicit and implicit needs using the Design Science Research (DSR) method (Hevner et al. 2004). The toolkit prototype follows a novel approach of generating new solution information in the form of completed solutions and recommends these solutions to users based on their feedback. The feedback-based interface reduces the number of interactions needed for the user to find the solution. The application context for the toolkit in this study is for *storage cabinets*. The context conveniently demonstrates the underlying design principles and theory as designing cabinets can have a large solution space (infinite variations), can be visualized as a 3D model and the resulting solutions can be further digitally fabricated. The artifacts and results from the study are easy to explain and communicate, and they can be further replicated in other scenarios. The toolkit was evaluated during the design process by observational studies conducted on potential users. It was also evaluated using an experiment that compared navigation between the prototype toolkit and a traditional toolkit used to design storage cabinets.

The toolkit generates finished designs of cabinets based on explicit needs entered by the user as well as implicit needs identified from iterative feedback from the user. It consists of three artifacts: A web-based toolkit interface to the user, an ontology for mapping explicit user needs to product design characteristics, and an algorithm to traverse through the solution space and categorize solutions based on how similar they are to the user. In each iteration, the user just selects a finished solution closest to the user's needs rather than designing the solution step-by-step. The toolkit then identifies the user's implicit needs based on the user's selection (feedback) and generates the next set of solution recommendations. Hence, it keeps generating solutions until it finds the right match to the user's need information.

The designed toolkit prototype has significant research contributions in the role of users and their involvement in innovation and design and contributes to the problem of focused navigation seen in both configurators and user design toolkits. Finally, the designed artifacts extend previously 'known solutions' of recommender systems and derive a variant for toolkits for user innovation and design. It thereby follows an exaptation approach of design, taking a known solution for a new problem (Gregor and Hevner 2013).

## Theoretical Foundations

### *Need-Solution Pairs and Design Decisions in Toolkits*

Problem-solving research has traditionally assumed a sequential process of identifying a need, formulating it, and then searching for an optimal solution to the problem. It is similar to the typical design process for constructing artifacts followed as a research method for this study as well (Peffers and Tuunanen 2007). Another approach to problem-solving involves first proposing solutions and identifying any needs they trigger. In these cases, the problem identification comes after discovering a solution. Hence, there is a need landscape and a solution landscape that are connected by need-solution pairs for innovation (von Hippel and von Krogh 2013).

One way of identifying various need-solution pairs is to formulate broad and flexible problems purposefully. These approaches are used in lead user studies (von Hippel 1986) where the focus is to identify need-solution pairs that may or may not fit (perhaps after some modification) the need-solution landscape of the firm. The positive deviant study approach also uses a similar technique of first identifying existing solutions that meet some people's needs and then checking if they fulfill other people's needs (Krumholz et al. 2011).Using algorithmic searches to find solutions for problems is another way to find need-solution pairs that are suitable when the problem is well structured. Here, problem formulators can convert ill-structured problems into well-structured problems (Simon 1973).

The process of users developing needs and solutions for innovation can involve several design decisions. Users in this process can easily get overwhelmed, confused and frustrated, when dealing with excessive choice and product related information, resulting in sub-optimal decision making (Huffman and Kahn 1998; Mitchell and Papavassiliou 1999). Increasing options that result in further product variations turn the positive effect of variety into negative as the complexity increases, and users need to be more involved in the process and deal with a large number of design questions and options (Teresko 1994). Different types

of consumer confusion occur because of configuration overload when a consumerperceives a configuration task to be (1) too complex, (2) have unclear options, (3) have unsettling options, or (4) too similar options to be differentiated (Matzler et al. 2007). Collaboration in user communities has been suggested to reduce mass confusion when dealing with customized products (Piller et al. 2005).

From the perspective of rational choice theory, mass confusion exemplifies situations in decision making, where decision makers rely on bounded rationality because the given problem is too complex to be solvable analytically (Simon, 1955). Decision makers apply heuristic procedures, which lead to results which cannot be called optimal any more, but instead satisficing (Selten 2001). We define non-expert users as users with little knowledge about suitable need-solution pairs and proper procedures to reach them, hence make satisficing decisions in contrast to experts who by their experience or training, are more competent and knowledgeable to act in such a situation.

### *Focused Navigation in Toolkits*

Configurators require five core capabilities to offer the right solution space to users. These are flexible navigation, focused navigation, benefit-cost communication, easy comparison functionality and user-friendly product space description (Trentin et al. 2013). Out of these, the capability of focused navigation is of interest to our research. Focused navigation is the ability to focus a user's search quickly in the solution space on finding the best match to the user's needs (Trentin et al. 2013). It is a challenge for non-expert users who have a large potential solution space. Toolkits achieve this at the cost of design flexibility by reducing the size of the solution space. Users then have much lesser information to process when making their decisions and can spend a long time in absorbing this information, building up their preferences and thus make better decisions (Bettman et al. 1998; Syam et al. 2008). An approach that can result in focused navigation is option ranking, where users can order the configurable options by their importance. As the user makes a choice, the solution space gets reduced for the further sub-choices in the solution space (Salvador et al. 2009). Another choice is to have starting points close to the customer's ideal solution. It will decrease the number design decisions that need to be taken to arrive at the solution (Randall et al. 2005).

The literature on mass customization toolkits also suggests different interfaces for different types of users. Expert users are very familiar with the product, and they would like to make design decisions directly. Non-expert users need support in making design decisions and are more concerned with their needs rather than the exact design decisions. They prefer an interface where they can express their needs rather than directly modify the design attributes (Huffman and Kahn 1998). In innovation toolkits, focused navigation can be achieved by reducing design decisions through generative algorithms that automate some design steps and only present users only those design decisions that are relevant to their needs (Naik et al. 2016). Users are thus relieved from the additional workload, which does not contribute to innovation because it is connected to routine operations, which distract users from using their creativity instead of supporting it. For example, algorithms in innovation toolkits can generate combinations of building blocks that are valid solutions so that users do not have to make these time-consuming combinations themselves. They result in solutions that were previously unknown and hence lead to innovation, for example in 3D printing (Naik et al. 2016) and business models (John 2016).

### *Recommender Systems*

Recommender systems (RS) are an established technology for decision processes with suggestions of products that fulfill customer needs within a greater space of potential products (Resnick and Varian 1997). RS have a broad application area, and they are currently in use in many internet firms' offerings. For example, Amazon, YouTube, and Netflix use them to suggest certain products or content from a large pool of users that they may also like based on their past preferences. The actual role of RS within an information system, the underlying data, and techniques used can vary widely. Potential data sources can be a product that is chosen and its characteristics, users personal characteristics such as demographic data, past transactions, etc. (Ricci et al. 2011). Burke (2007) describes six RS approaches that are listed here: 1) content-based, 2) knowledge-based, 3) community-based, 4) collaborative filtering-based, 5) demographic-based and 6) hybrid systems (Burke 2007). Out of these six approaches, knowledge-based recommendations and its sub-category constrained based recommender systems are described below as they form the theoretical basis for the design of the artifact.

Knowledge-based recommender systems (KRS) have specific domain knowledge on how certain item characteristics fit users' preferences. They do not require a significant amount of statistical data or information about the user and operate within the predefined knowledge base. KRS are ideal for scenarios where other relevant recommendation data sources are unavailable. They are particularly suitable for complex products where non-expert users do not have knowledge on item characteristics (Ricci et al. 2011). Furthermore, they are a commentary to other forms of RS, making them extendable to form future hybrid systems (Burke 2007).

KRS can be implemented using two basic techniques that differ in the selection process used for the recommendations. The first technique uses case-based RS, where the KRS uses a similarity measure to compare items and their characteristics with user preferences. The second technique uses Constraint-based Recommender Systems (CRS). They convert user preferences into constraints based on rules formulated into the system. These constraints are used to filter out and select recommendations that are shown to users (Felfernig and Burke 2008). While KRS has not been researched as much as other RS variants, they still are highly relevant. CRS is a relatively popular form of KRS (Jannach et al. 2012). As these RS rely heavily on the knowledge base and rules within the systems, the structure of the database and methods for entering data need to be planned and executed carefully.

Extracting user preferences from their interaction with the system is a challenge. Personalized interfaces that have optimized user interaction dialogues are one way of extracting user preferences. Another approach is using the critiquing technique, where users do not need to specify all of their requirements at the beginning of the process. Instead, they build their preferences by going through many recommendation cycles and giving their feedback at each step. In each iterative step, the system presents a small number of options and users can give their feedback. The user continues reviewing different iterations until a matching item is retrieved (Ricci et al. 2011).

This critiquing technique with its iterations is similar to the iterative use of a toolkit and its associated design questions. The design of the toolkit in this study follows the model of presenting recommendations based on a constraint-based knowledge base that is refined by iterative feedback. However, the toolkit should also be able to automate design steps and generate recommendable solutions. The upcoming sections describe these techniques.

## Research Design

The study addresses the research question of how a toolkit can enable non-expert users to search through the solution space and find solutions to match their needs by designing artifacts following a DSR approach. Design science research is a process to continuously build-and-evaluate a set of artifacts (Hevner et al. 2004). Our main goal was to develop novel and creative artifacts within the constraints of problem-solving (Baskerville et al. 2016) through design iterative evaluation and refinement of the artifacts developed through the search process. It follows Peffers et al. (2007) and consists of six steps.

The first step of the research design was to identify the research problem. The problem with existing toolkits was two-fold: (1) toolkits for large solution space have many design steps, which was not suitable for non-expert users (2) toolkits for design did not provide an easy way for users to articulate their implicit needs.

The next step of the research design set the objectives for the solution that would outline the requirements for the artifact. The first objective was to design a toolkit where the user had to perform fewer design decisions (MacLean et al. 1991; Naik et al. 2016) than in the traditional toolkit. The second objective was to design a toolkit, which could incorporate the concept of need-solution pairs (von Hippel and von Krogh 2013) described earlier. In other words, the objective was to design a toolkit, which generated and recommended possible solutions to simplify solution space and enable non-expert users. It allowed users to form need-solution pairs, either when they stumble upon a solution matching their implicit needs that they were unaware of earlier, or when they could not express through a traditional toolkit's user interface.

The design required choosing a context for the new toolkit, in which user design toolkits exist, and these toolkits require a significant amount of user involvement. We selected a toolkit for designing storage cabinets. Designing simple cabinets with rectangular shelves of different dimensions can easily run into a large number of variations. In a traditional toolkit, users make multiple design decisions with various design

options. An example can be deciding the number of columns, the number of rows for each column and their dimensions, choosing a door for each shelf, the type of handle, etc.

Building a generative design toolkit is a new concept, but draws upon various fields. The design requirements were inferred from the theoretical foundations discussed above and adapted for user design. A web-based toolkit prototype for users to select pre-designed storage cabinets was developed. The cabinets were designed by the toolkit to match users' explicit and implicit needs. The prototype web-based toolkit consists of three artifacts: 1) a web-based front end user interface for presenting recommended solutions and visualizing them in 3D 2) an ontology of user need functions mapped to product characteristics, and 3) an algorithm to traverse through the solution space, generate solutions and recommend appropriate samples to users.

The toolkit was trialed using fictitious user needs for demonstration, and the resulting designs were checked with the configured specifications to identify and eliminate any technical errors. The toolkits also logged details about the generated solutions and recommendations at major steps of the algorithm and compared to ensure that the artifacts functioned as per their theoretical design. The user interface was also tested with various boundary conditions to see if they were correctly displayed. These steps formed the technical review of the artifacts that ensured they operated correctly as theoretically intended.

Preliminary evaluation of the artifacts was conducted using observational studies on users, at regular intervals. The trials involved three observational studies, each with one user and two observers. In each of the three studies, the user was observed while using the toolkit, for approximately 20 minutes and their usage behavior was logged. The user was then also interviewed with various open-ended questions that explored the user's usage perceptions at different stages of the trial with the toolkit. Each user was also asked for feedback on the construction of the toolkit, which guided the design of the artifacts. Iterative cycles of demonstration to potential users of the toolkit contributed to fine tuning the toolkit and building its design knowledge.

Furthermore, the toolkit was also evaluated by experimenting with two groups of randomized participants (Christensen 2007), where participants used the designed prototype toolkit and a traditional customization toolkit to design storage cabinet. Sixteen participants between ages 23 and 30 from a non-design background, but technically literate were selected to participate as non-expert users. The interactions of the participants were logged to identify usage patterns. To collect feedback on the usage of the toolkit, we followed the method of problem-centered interviews ("The Problem-Centred Interview - Andreas Witzel, Herwig Reiter - Google Books" n.d.), which was performed in a subsequent workshop where the participants were asked questions on their interactions and the reasons behind their exhibited usage of both the toolkits and proposed design improvements if any. Their responses were recorded and analyzed to improve the toolkit further and improve the comparison between the toolkits. The results of these pilot evaluations are presented in this study.

## Artifacts

This section presents the first part of the results of the study conducted using design science research, the artifacts that resulted in the design process. The DSR study constructed three artifacts that are loosely coupled(Simon 1969) but together form the Feedback based IteRative Solutions Toolkit (FIRST)[1] a web application toolkit, to meet the objectives of this study. FIRST is a toolkit to customize storage cabinets for the non-expert user. It generates all solutions in the solution set and then uses a critique based recommender system to recommend solution samples to users. The advantage of this toolkit is that it designs the solutions for the user and focusses navigation for the user by only presenting solutions that are likely to match user preferences. Non-expert users also interact with finished solutions rather than design their solutions from scratch. Therefore, they are inclined to select a solution that is good enough rather than stop the design process before findings a satisfactory solution.

Designing the toolkit needed a well-defined and modular architecture that allowed it to be functional while being flexible to improvements and maintenance activities. The model-view-controller architecture pattern was adopted which separated the toolkit into three artifacts for each of the three layers: the model layer, the

[1] The development version of FIRST is accessible at http://reconfig.class.wi1projects.com

view layer, and the controller layer (Leff and Rayfield 2001). Model-view-controller (MVC) also known as the Presentation-Abstraction-Control (PAC) design pattern (Coutaz 1987) is a programming model and implementation infrastructure that allows the flexible design of the toolkit. It allows modifications to the partitioning of the toolkit, made in the initial stages of design. Its key idea is to separate the user interface, the underlying data behind the user interface and the logic controlling the application. Following this approached allowed drastically changing the application's look and feel without changing the data structures and business logic as much. Each of the three artifacts corresponds to a layer of the toolkit. The following sections further describe the three artifacts.

### *Artifact 1: Visual Feedback Interface*

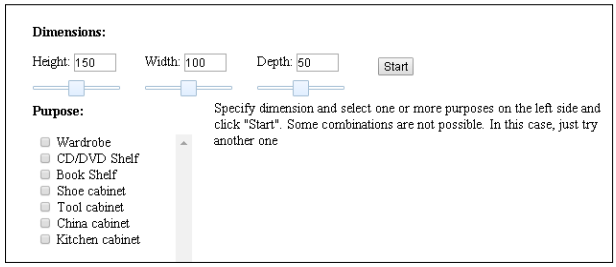
The traditional model of the toolkit (von Hippel and Katz 2002) provides users the ability to learn by doing through trial and error cycles. FIRST, on the other hand, learns about the user's needs through trial and error cycles of suggesting different designs to the user. FIRST explicitly asked some of the user needs are through a basic form while it inferred the other implicit needs from the user's choices. This method leads to the incremental building of the user's needs through the selection process followed in the toolkit.

This selection process follows the critiquing method, a type of knowledge-based recommender systems (KRS) to interact with users. This method, initially found in case-based reasoning for conversational dialogs is also used in KRS and CRS (Burke 2007) While they are used to present users with different options of products so that they can provide feedback by critiquing the options, FIRST presents users a sample of generated solutions and collects feedback on them. It used this feedback to identify implicit needs and match them to design characteristics of the solution. The process is described in further detail in Table 1.

As the point of contact of the underlying layers with the user, it has an especially important role in the design of the toolkit FIRST. In such a scenario, it is important to use lightweight and modern technologies, i.e., they give users a quick response time in their interactions. The web interface is browser-based. It generates and filters solutions as well as visualizes them in 3D. The toolkit assumes that users have explicit and implicit needs, which it needs to capture to find users matching solutions.

In addition to the feedback-based interface, FIRST also allows users to change certain product characteristics that are independent to the generated recommendations, such as the type of material used for the cabinet and the handles that are used. Changing them does not affect the generated solutions and associated recommendations.

Users can at any point of time save multiple designs that they like and view them later. Hence, the user can potentially run through many sets of iterations and save all designs that they find interesting before revisiting them and deciding which design(s) they would finally like to purchase. The simplified flowchart below describes these steps in Figure 1.

| | |
|---|---|
| **Step 1: Input form for explicit needs**<br><br>On accessing the toolkit URL, FIRST asks users for their explicit needs, which they can enter by filling up a form. They can enter height, width, and depth of their needed cabinet and choose between one more functional needs they expect to fulfill with the cabinet. |  |

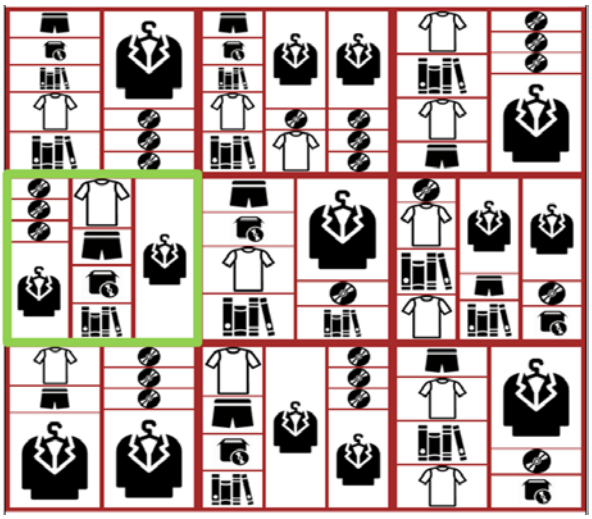
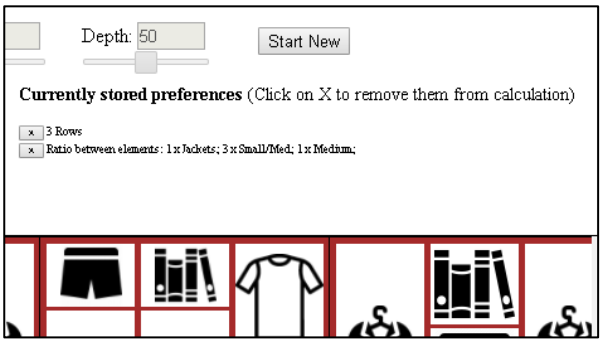
| | |
|---|---|
| **Step 2: Nine sampled solutions generated by the toolkit**<br><br>On clicking start, FIRST converts the chosen explicit needs into design criteria that act as constraints for the solution and then generates a large sample of representative solutions from the constraint bounded solution set.<br><br>It then makes a pre-selection of nine (optimum number of options from user evaluations) solutions from the solution set and presents them to the user. The user can then choose any one of these solutions by clicking on them. |  |
| **Step 3: Visualization of selection option in the browser in 3D**<br><br>FIRST highlights the selected option and visualizes it in 3D on the left using a 3D rendering engine (three.js). The user may zoom in and pan the 3D representation of the cabinet as well as toggle a 2D display of the cabinet.<br><br>The user can then re-click the selected solution to generate solutions similar to the one selected. The user then goes back to Step 2 and works with a new set of sampled solutions.<br><br>On performing this step, FIRST stores the characteristics of the selected model as implicit needs and uses them to calculate new solution recommendations for the user. FIRST displays the implicit needs that are stored on top of the options, so that users can always erase any of the implicit needs that were wrongly stored by the toolkit. |  <br>  |

**Table 1: Web interface of FIRST for visualizing solutions and capturing feedback**

### *Artifact 2: Solution Generation and Recommendation Algorithm*

FIRST relies on an algorithm with three parts for generating different solutions and filtering them based on user feedback. The first part validates the explicit needs directly entered by the user based on stored rules that define maximum sets of valid combinations.

The second part generates solutions based on the explicit needs. Each solution is a cabinet that consists of components of elemental shapes, which are building blocks of the cabinets. The building blocks map to different functionalities entered in the explicit needs, and their dimensions are modifiable within certain tolerance levels. The algorithm generates all possible sequences of combinations of these blocks that match the criteria given to them and aesthetic constraints put on the solutions. It uses a simple "box matching" approach that follows a recursive trial and error principle similar to a depth-first search. It attempts to find a solution by inserting the modules into the predefined columns and saves every successful attempt as a solution model. If not, then it modifies the modules within their tries again. The algorithm generates finer variations in the solutions (such as open or closed doors, types of inner drawers, etc.) after the other implicit needs have already restricted the designs considerably at the end of the process.

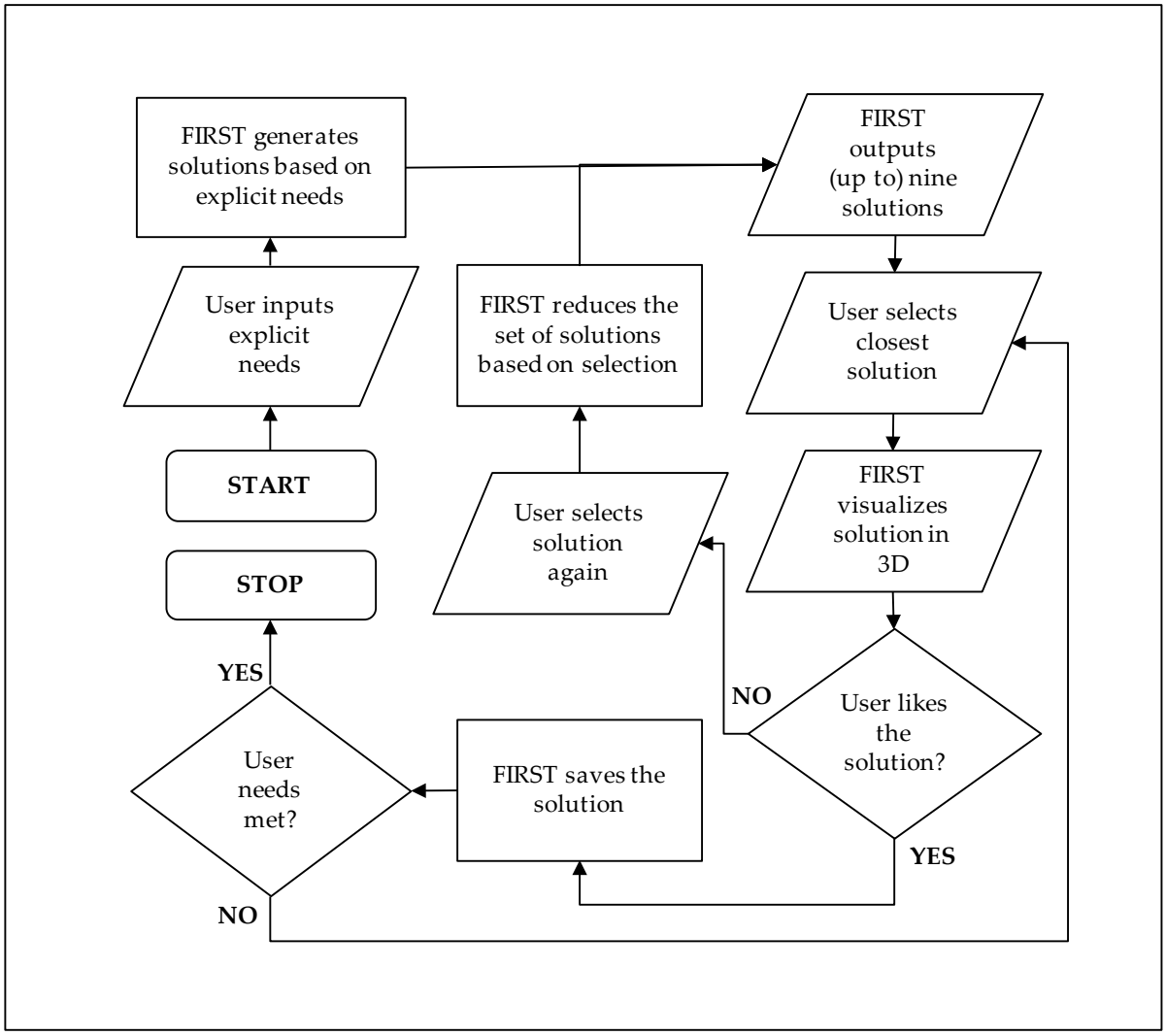



**Figure 1: Simplified flowchart of user interactions with FIRST**

The third part deals with the reduction of the solutions into the sample presented to the user and filters out gradually solutions based on implicit needs of the users. The algorithm samples a limited set of solutions

with the greatest diversity and recommends them to the user. The algorithm creates a set of buckets to categorize different solutions based on characteristics that identified to create the most diversity. It then distributes all solutions across these buckets. Once it has distributed the solutions, it picks one solution from each bucket by calculating the solution that has the farthest distance from the average of the solutions of the bucket. The algorithm calculates the distance by comparing different sequences that are part of each solution. Furthermore, once an entry is stored in the implicit database, it represents the user's implicit need, and the algorithm uses the entry to filter out all solutions that do not meet this implicit need.

### *Artifact 3: Ontology for Need-based Recommendations*

Constructing FIRST requires a conceptualization of user needs and design characteristics of storage cabinets (Genesereth and Nilsson 1987). The conceptualization draws from objects, concepts, entities, and their relationships in the area of user needs and design, derived from literature and theory discussed earlier. An ontology for need-based recommendations is an artifact that can be used in future applications in information systems. An ontology is a formal specification of the types, properties, and interrelationships of the entities that represent the relevant topics in existence. By defining an ontology to represent, there is a common vocabulary that represents the conceptualization which can guarantee consistency between different agents applying this knowledge (Gruber 1995).

The needs-based recommendations ontology is a representation of needs and solutions and other concepts that are a part of the toolkit. It stores needs and rules connecting them to design characteristics in FIRST, the toolkit that was developed. While FIRST is a toolkit for customizing cabinets, the ontology has components that can be generalized to other scenarios where users give feedback by visual interaction with the solutions recommended by the toolkit. The ontology consists of classes that divided into three groups, namely data classes, presentation classes and logic classes. Three main data classes relate to the data stored in the toolkit used for solutions generation and recommendations. These are the explicit database, implicit database, and model classes. These classes represent the constraints used to filter out only those cabinets that meet user needs, and they represent the cabinets themselves.

The view classes consist of input reader, output writer, and object visualizer. The classes deal with input fields where the user can enter explicit needs, representation of generated options and visualization of a selected solution in 3D. The logic classes include model calculator and model reducer, which mainly consist of functions that generate different solutions and reduce them into the set of up to nine solutions shown to the user in each iteration. While all the classes listed above are very important to the functioning of the toolkit, a few of them are highlighted because they deal directly with the needs and recommendations.

**Explicit Database:** The explicit database is the class used to store all the information about explicit user needs that users can themselves enter into the toolkit. It also includes all the fixed parameters that have been set in the toolkit that users cannot normally modify. The algorithm needs these parameters, and the toolkit administrator can modify them as required. Explicit needs entered by users can be stored directly in the form of cabinet characteristics such as height, width, depth, material, handle, etc. It also includes parameters set by converting the explicit needs into design parameters using rules within the toolkit. These rules affect minimum and maximum conditions of the dimensions, constraints on the compatibility of different elements, etc.

**Implicit database:** The implicit database is the class used to store all the implicit needs identified by FIRST during the iterative selection process. FIRST builds these implicit needs by constructing their preferences, to determine the preferences sub-consciously selected by the user. Qualitative feedback during evaluations ranked the elements in the implicit database class on their importance. Users listed design characteristics that differentiated different solutions. These characteristics were used to identify implicit needs as a user selected a particular solution in each iteration step. Therefore, every time the user selected a solution, the top ranked implicit need that the solution covered was recorded. These needs were then shown to users so that they could always be unselected.

**Input Reader:** The input reader class contains all elements related to user modification of the generated solutions. It collects explicit needs from the user and visualizes the identified implicit needs for the user. This class also validates the explicit needs entered by the user by checking on the dimensions entered and the purpose functions selected. It interfaces between users and the other classes related to model calculation. Once FIRST validates the explicit needs, the input reader contains rules that translate user

needs into design parameters and store them into the explicit database. So for example, an explicit need of a wardrobe would mean that FIRST chooses design parameter IDs 0, 2, and 3 while an explicit need of a shoe storage will mean that FIRST chooses the parameter ID 1. These IDs are converted to valid option intervals for underlying design parameters and define the boundaries between which solutions can be generated by the algorithm.

Each cabinet solution generated is stored using the solution model. It contains all the necessary elements to that store the dimensions of the cabinet. The cabinet model links to other structures for options that are unique to the different parts of the cabinet (such as doors etc). They have variables indicating the elemental blocks, their dimensions, as well as handle and material details.

## Evaluation

The evaluation of these artifacts forms a critical activity of the research method as it provides critical feedback to the design process and indicates how well the artifact supports the problem. FIRST was evaluated on a regular basis during the design process, as well as after the prototype reached a stable version to evaluate the design of the artifacts. The study conducted two types of evaluation activities. The first was a set of three preliminary observational studies on users of the toolkit, during the design process. It was followed by an experiment conducted on participants who used a traditional toolkit for creating custom cabinets and compared it with FIRST. These evaluation activities conducted on the artifacts are presented in the following sections.

### *User Testing*

The first observational study was conducted with a potential user in a workshop that lasted 60 minutes. This study showed that the user found too many options at each step confusing and it had to be limited. Moreover, the importance of showing significant variations between the options became apparent. Users implicit needs needed to be set in an order based on the importance to users so that they can quickly filter them out through their selections and focus on the minor variations. The user also pointed out suggestions to improve the model visualization and validated add-on features such as a save function to store the currently selected model and to scale up the 3D design whenever required.

The second user evaluation was another 30-minute workshop. This workshop also validated the feedback received from the previous evaluation regarding better visualization of the 3D model and better diversity in the recommendations. The user also provided further inputs on the type of explicit needs, their corresponding purposes, and design features and gave further ideas on better presentation of the solutions.

A third user evaluation study was conducted with two users, where each used the toolkit for around 20 minutes. One of the users had specific needs on the design of the cabinet required while the other had no clear goal in mind. Both users were optimistic of the toolkit model where finished solutions are recommended to users. The user with clear needs required more interaction possibilities and wanted the toolkit to be less restrictive, while the other user liked the diversity in different solutions. They both also preferred some of the additional features such as the toggle between 2D and 3D and saving multiple solutions into a history. These features were then incorporated into FIRST.

### *Comparative Experiments*

FIRST was then compared with a traditional customizing toolkit (TC) to design storage cabinets in an experiment. Screenshots of the two toolkits can be seen in Figure 2. Sixteen participants between ages 23 and 30 from a non-design background, but technically literate were selected to participate as users. They were familiar with web applications and the concept of mass customization but had no prior experience in designing storage cabinets. TC has a user interface typical to mass-customization toolkits, where the user makes design decisions in a sequential order and selects options at each step. The user first enters the overall dimensions of the cabinet and then decides the number of columns for the cabinet, the number of rows for each column and additional characteristics such as cabinet doors and door handles. Both the toolkits had every user action logged.

The experimenters were divided into two groups of eight participants. The first group of participants used the traditional configurator and then after they had finished, used the new toolkit. The order was then

reversed with the second group. In both cases, the participants were asked to design cabinets that matched their needs. They were given detailed instructions on the toolkit functions and process before they started to use the toolkits. Along with the instructions, they were encouraged to explore the toolkits and ask questions for clarification. The users' interactions with both the toolkits were then logged, and their experiences with both the toolkits were collected in a 15-minute workshop session that was conducted with the participants. The workshop was conducted in a semi-structured manner, with the following leading questions "How was the design process using FIRST/TC?", "Which toolkit did you prefer and why?" and "How did your preferences change during the design process?" These questions were then followed up with additional probing questions based on participants' responses. The responses were then analyzed to identify emergent themes corresponding to the research question.

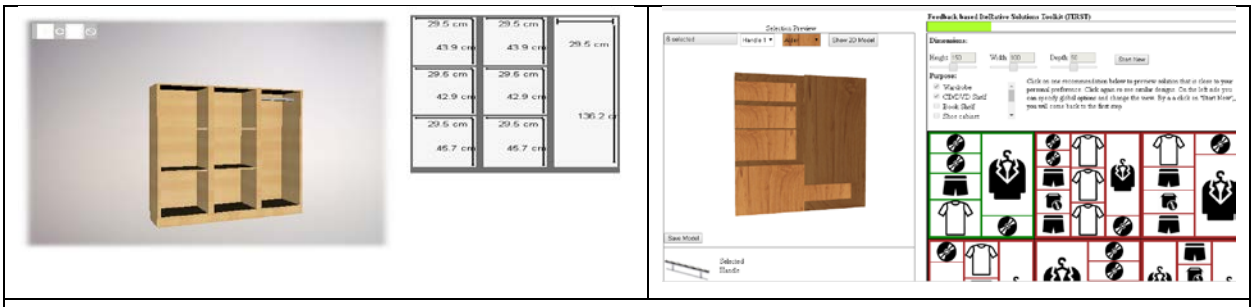


**Figure 2: Screenshots of the two toolkits compared (TC vs. FIRST)**

## Results

Analyzing the paths of both the toolkits showed the expected usage difference between the toolkits. With TC, users showed a clear direction they follow with sequential design decisions. There were few trial-and-error cycles, which only occurred at the end of the design process. Some of the users also did not complete the design and just stopped the process, as they were frustrated by the many design decisions. With FIRST in contrast, users were already working with completed solutions, and through their selections, the toolkit identified their implicit preferences. Often users went back a step by deselecting the implicit preferences identified.

The average time users took to find a solution using FIRST (178.50 s) was on lower than the average using TC (358.05 s), but there was a significant variation in the paths they followed. Users of TC needed much time to complete the first few steps and then on began to shorten the time with each step. It implied that the TC needed some time before users could comprehend the configuration process and start working. The structure of the TC also forced users to perform a larger number of design decisions as they had to design the geometrical shapes themselves. On the other hand, with FIRST, users could finish the first step of entering their explicit needs relatively quickly and spent more time trying to improve their models. Some users quickly finished the design process while the others spent longer in exploring different solutions to pick one that exactly fit their needs. Users in both toolkits spent considerable time on selecting the different material and door options, implying a strong desire to influence the model directly through their interactions.

The workshop revealed some reasons for this user behavior. The participants could easily relate to the general problem situation, as they were familiar with the experience of moving into new rooms or apartments and purchasing customized furniture. Furthermore, they were briefed about designing a cabinet they would like to have. Hence, they were building fictional cabinets, but they had different levels of involvement in the design process. Some participants indicated that they felt a personal bond of creating solutions with TC, which comes from being involved in the systematic design process. They lacked this feeling when using FIRST. However, they found the recommended solutions of FIRST to be great starting points from which they could optimize their designs. Participants who did not have strong preferences for the cabinets (explicit needs) on the other hand, preferred the generated solutions of FIRST to manually designing with TC. They found the sequential design process of TC overwhelming with too many design decisions and were able to converge to a good enough solution using FIRST. Some illustrative quotes highlighting this difference can be seen in Table 2.

| Toolkit | Codes | Illustrative quotes |
|---|---|---|
| FIRST | unspecific needs<br>satisficing | "The toolkit (FIRST) was better because I did not know how my cabinet should look like" (EP1)<br>"I could not finish designing the cabinet (with TC) because it took long. I was able to find many cabinets with the other toolkit I liked quickly." (EP2) |
| TC | personal bond<br>specific needs<br>maximizing | "I did not really design my own cabinet because the software designed it for me" (EP3)<br>"The toolkit did not design the cabinet exactly the way I wanted" (EP4)<br>"I wanted exactly certain dimensions, and I could design my cabinet exactly that way" (EP4) |

**Table 2: User responses towards FIRST and TC toolkits**

## Discussion

In this study, a smart toolkit (FIRST) was designed (based on three artifacts) and evaluated with potential users and qualitative workshops. It is a novel exaptation, as it combined existing solutions and applies it to the new problem area of toolkits for user innovation and design (Gregor and Hevner 2013). The toolkit contributes towards design for innovation toolkits as it demonstrates the automation of two aspects of the innovation, (1) developing new solutions and (2) traversal through the generated solution space. Tthe generative algorithms automate solution generation through domain specific rules that generate all possible combinations. It differs from design theory on computer generation of ideas (John 2016) as the solutions are developed by finding all possible combinations of building blocks that are defined in the toolkit. This approach can be used in empirical contexts where modular building blocks have been defined (such as building innovative electronics with Arduino modules). The generated solutions need to be further traversed or evaluated to find the right solution for the user. Here the toolkit improved on tried and tested critique based constraint recommender systems, by the use of user feedback from visualizations to traverse through the generated solution space for user innovation and design. This form of evaluation is suitable in contexts where users can visually inspect solutions and come to a quick conclusion. It differs from using the crowd for evaluation as suggested by John (2016), as the needs are defined by the individual rather than a collective. The paper overall adds to the diversity in design science research and has theoretical contributions for the design of innovation toolkits as outlined in Table 3. We believe the designed artifacts make a valuable contribution to innovation toolkits as it demonstrates "not how things are but how they might be" (Simon 1969, p. xii) a major perspective of design science research (Rai 2017).

The toolkit inverts the traditional problem-solving approach where solutions follow problem identification and instead generates the solution space first, thus implementing the creation of need-solution pairs in its context (von Hippel and von Krogh 2013). As a smart toolkit, it enables non-expert users by reducing the design decisions and also the options for the decisions that they would have to make (Naik et al. 2016). It thus takes an active role in the search process in comparison to the passive role other toolkits have played in user innovation since their conception (Baldwin and von Hippel 2011; von Hippel and Katz 2002; Moeslein and Fritzsche 2017). Users just have to explore their need space and decide if the recommended solutions match their needs and do not have to design solutions from scratch, component by component. The value created by the smart toolkit in enabling non-expert users by reducing their search decisions is depicted in Figure 3. Considering the users with specific needs who were seen to prefer to make design decisions directly, we suggest a dual approach that allowed direct modification and recommendations.

The research design had many iterative development cycles with continuous evaluations. Including many evaluation points during design were invaluable in ensuring that the designed artifact matched the identified problem in its real world context. Feedback from these evaluation studies thus brought challenges in design, and the user interface and architecture had to be frequently changed. The results of the assessment show that toolkits based on recommendations were considered in general as a novel approach and helpful to the non-expert user. FIRST provided solutions faster than the TC and hence led to focused

navigation, while it had inconclusive results regarding user satisfaction. Hence, the generated solutions seem to be an excellent way to generate solutions as starting points when the user has predefined needs or for complicated design decisions that non-expert user would rather not make. The users who had needs in mind also wanted the ability to modify the generated solutions directly, even if it was by using simple functions such as scaling the cabinet etc. Not providing this capability risked negative reaction towards the toolkit that outweighed the benefits.

| **Findings** | **Theoretical Contributions** | **Type of Theory** (Gregor 2006) |
|---|---|---|
| Web interface for communicating needs and visualizing in 3D | The web interface artifact can be used to describe future interfaces for toolkits which rely on visual feedback | Design and Action |
| Underlying ontology for needs-based recommendations | The ontology artifact provides a structure for representing modular products in information systems | Design and Action |
| Algorithm for solution generation and reduction | The algorithm artifact can be used to design solution generation and recommendation systems | Design and Action |
| Users can find solutions faster with toolkits that generated and recommended solutions than traditional toolkits. | Supports the proposition that toolkits with generative algorithms can simplify solution space for non-expert users | Prediction |
| Users do not necessarily find better solutions with toolkits that generate and recommend solutions provided than traditional toolkits. | Supports the proposition that toolkits with generative algorithms can simplify solution space only for non-expert users with implicit needs (von Hippel and von Krogh 2013) | Prediction |

**Table 3: Theoretical contributions of the study**

It implies that some of the users have a strong desire to influence the model directly through their interactions. One potential reason for this could be the personal experience of the users, who are more familiar with making choices directly than relying on recommendations. Another reason could be the higher relative importance of these options compared to the others – an opinion that surfaced later in the free discussion round where the candidates liked the recommendations in the initial stage, but soon felt restricted by the limited interaction possibilities. The experiments showed that a majority of the users changed their preferences during the configuration process. It is in line with the literature on preference construction during the customization process (Slovic 1995).

The adjective “smart” often occurs in literature and media currently with the expansion of digital technologies across industries as well as propagation among end-users (Oks et al. 2017). The practical implications of the study are clear as it demonstrates an application of a smart system that enables users to innovate by generating and quickly finding solutions. While rule based systems have made way to machine learning (Jordan and Mitchell 2015) in many application scenarios, smart systems that replicate patterns found in data may not be ideal for generating novel solutions. In today’s context of flexible innovation technologies such as 3D printing and other digital fabrication (Snyder 2014), the large solution space is not readily available to users who are not willing to become experts and even training children and other future innovators (Iivari et al. 2016). The number of design decisions which make up the search through the innovation solution space needs to be managed without letting go of previously unexplored design possibilities. The artifacts developed in this study can be migrated to other contexts to generate new combinations of solutions to assist non-expert users. A toolkit that generates solutions goes beyond the established notion of toolkits. It can let users focus on their needs and matching solutions, both partially or entirely, and at the same time find novel solutions not anticipated by the manufacturer (von Hippel 2001).

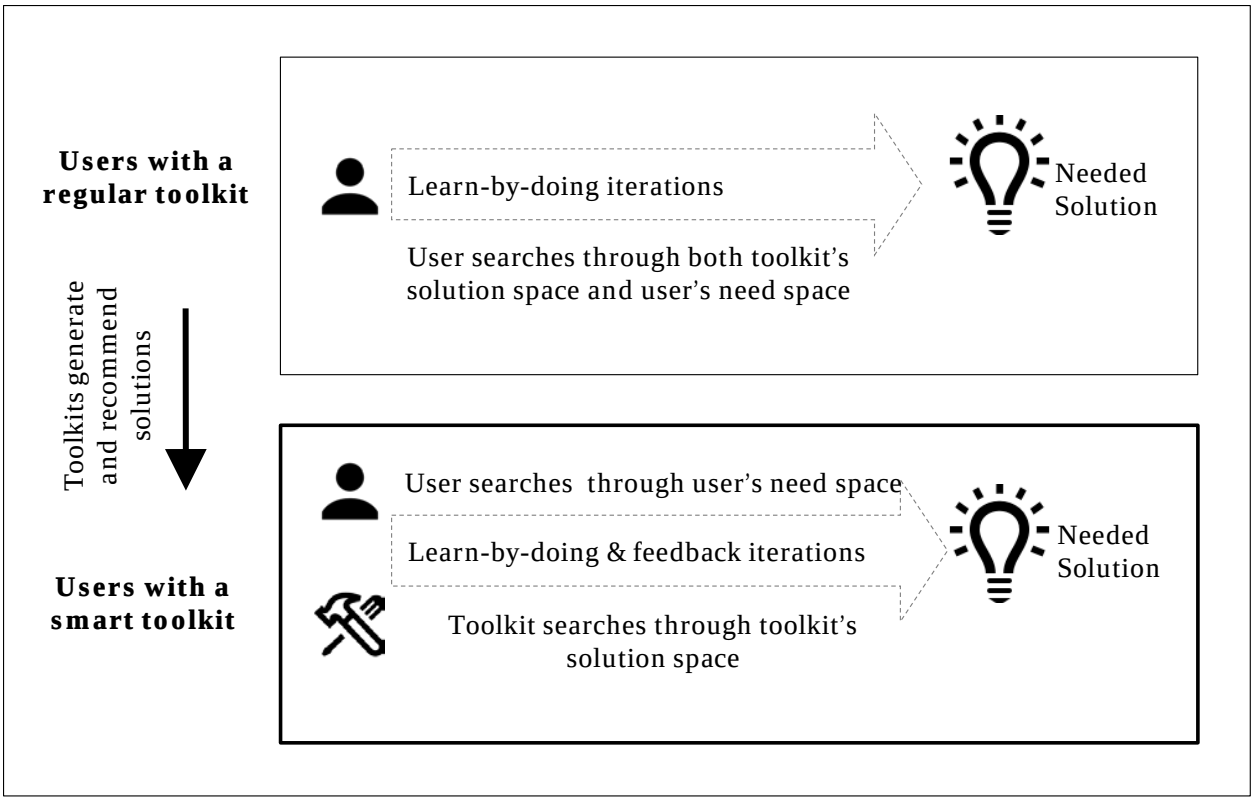



**Figure 3: Democratization innovation with a smart toolkit**

## Limitations

As this study takes a step into a little-developed research area, it has various limitations, some of which can be reduced following further iterations of the study. The design of the ontologies can be made more generalizable into contexts that are more complex and evaluated. The experiment conducted to evaluate the toolkit follows a single case study design that can have a tendency of showing carry-over and order effects, where the results from one experiment phase carry-over into the next step and affect its results. Further experiments could avoid these issues by using larger sample sizes and more detailed experiment designs, with testable hypotheses. The experiments conducted as part of the evaluation studies were relatively small and homogenous, and this affects the generalizability of the results gained. Future research can continuously conduct experiments with a larger number of participants for better generalizability of the results. Another approach could be to distribute the toolkit among online communities of potential users and get a larger sample size of participants for quantitative research on discovering implicit needs by also incorporating features that provide users further guidance.

A design limitation of the toolkit in the study is that even though it had a flexible architecture, it ran on web browsers, using web-based JavaScript libraries with the processing done on the client system. This flexibility came at the cost of following architectures optimized towards performance. Scaling up this toolkit to scenarios with a lot more generated solutions may require performance optimizations to handle different variations.

## Conclusion

This study answered the research question of how toolkits with recommendations can enable non-expert users to search through the solution space by designing novel artifacts following the DSR approach. Three artifacts were designed which when put together form a web-based toolkit for designing cabinets that satisfy user needs. The toolkit operates differently from similar toolkits used traditionally for customization by generating solutions and recommending them to users. Users can directly state their explicit needs or

indirectly state their implicit needs by selecting the solutions closest to what they need. The toolkit identifies implicit needs based on their selections and uses it to refine the solutions and provide better recommendations to the user. The toolkit was iteratively evaluated and improved with potential users and finally compared to a traditional toolkit in an experiment. The toolkit indeed guided users faster to their needed solutions. Moreover, the evaluation suggested that users who had non-specific needs, with implicit needs they discovered later prefer to be recommended finished solutions. However, users with very specific needs were not satisfied, especially when the solutions provided were exactly meeting their specified needs.

To conclude, with these results we can claim that the design of toolkits can be enhanced in the future to generate and recommend solutions for users and provide a substantial competitive advantage to other toolkits, especially aimed at non-expert users with implicit needs. We believe that our approach adopted in this study can form a valuable building block for spreading toolkits for user innovation and design among users and better match users' needs with diverse and novel solutions. With digital fabrication technologies increasing the solution space, and toolkit support for effectively searching through this space, we envision innovation transitioning into understanding exactly the needs of our society and effectively translating these needs into toolkit information systems, thereby exponentially increasing the scope of digital innovation of the future.

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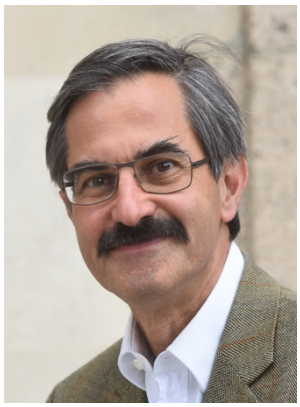

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Main research interests: design theory, design-oriented organization, design and neurosciences, design economics, design and creation, design history.

**Title of the Presentation:**

Introduction to C-K design Theory

**Synopsis:**

We first present the basic 'requirements' for a contemporary design theory. We analyze the basic notions of the theory (C-space, K-space, expansive partition…). Then we show how C-K design theory extends other design theories studied in the previous basic courses (Simonian tradition, German systematic). We conclude with some implications of C-K design theory.

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**Further readings:**

See references in "Chapter 4" above.

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