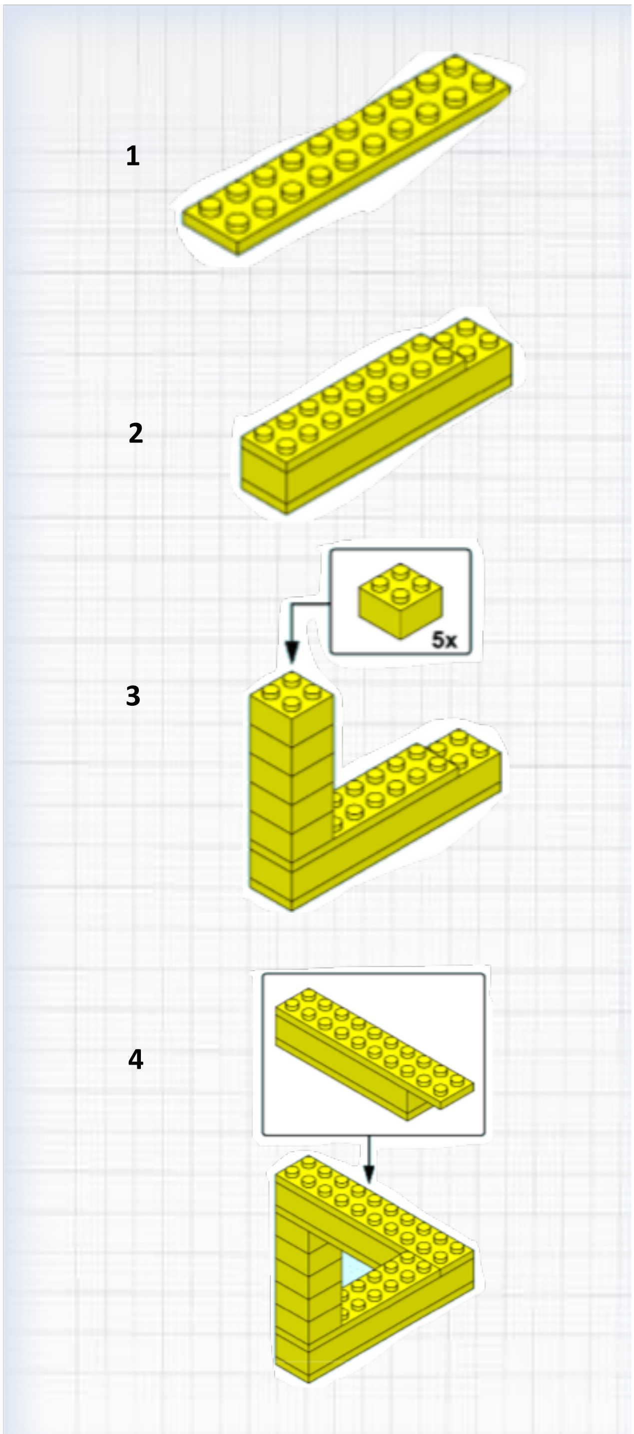
2ND TUTORIAL OF THE DESIGN THEORY SIG

31ST JAN – 2ND FEB, 2018 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

Alternative interpretations of C-K theory in math

Progress in axiomatic design

New colleges in design

MASTER CLASS & PUBLISHING IN DESIGN THEORY

MINES ParisTech
60 boulevard Saint Michel Paris
75006, FRANCE

design theory and methods for innovation

i3 institut interdisciplinaire de l'innovation

MINES ParisTech

PSL

DESIGN THEORY TUTORIAL – 31ST JAN – 2ND FEB 2018

Professorial college:

Professorial College		
Name	**Institution**	**Country, city**
Hatchuel Armand	MINES ParisTech	France, Paris
Kazakci Akin	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
Vajna Sandor	Otto-von-Guericke University	Germany, Magdeburg
Weil Benoit	MINES ParisTech	France, Paris

Organizer: Benjamin Cabanes

Speakers:

Speakers		
Name	**Institution**	**Country, city**
Brown Christopher	Worcester Polytechnic Institute	USA, Worcester
Cabanes Benjamin	MINES ParisTech	France, Paris
Hatchuel Armand	MINES ParisTech	France, Paris
Kazakci Akin	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
Subrahmanian Eswaran	Carnegie Mellon University	USA, Pittsburg
Vajna Sandor	Otto-von-Guericke University	Germany, Magdeburg
Weil Benoit	MINES ParisTech	France, Paris

Goal: Diffuse the knowledge produced in the DT SIG community in the last ten years – in the spirit of the “ten years” SIG plenary:

> *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 a basic science, Design Theory, 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, unified 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 that goes beyond the problem space complexity. These results give the academic field of engineering design a new consistent ecology of scientific objects and models, which allows for advanced courses and education. They have contributed to a paradigm shift in the organization of R&D departments, supporting the development of new methods and processes in innovation centres. Emerging from the field of engineering design, design theory development has now a growing impact in many disciplines and academic communities. The Design Society may play 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.*

We don’t claim a complete presentation of all that has been done in design but we focus on the recent works on design theory.

Participants can expect:
1- knowledge on the papers and results obtained in design theory
2- understand the logic “formal program / open program” of the SIG

Contents:

- Basic courses: 5 modules, made by professors of the Professorial college of the tutorial
- Master classes: interactive work sessions with (young or not…) researchers on their research topic and Design Theory in these research works.
- Advances: short presentation made by an expert on an advanced topic in design theory – typically: 20 minutes, based on a paper, presented by a professor. Topics to be covered are listed (see below)
- One session on “publishing in design theory”

Day 1: Salle Vendôme

Basic Course	Advanced Course	Master Class

Day 1 - 31 Jan 2018			
Timetable	**Type of Course**	**Title Course**	**Speakers**
9:00 - 10:00	**Workshop program + presentation of participants**		Armand Hatchuel & Yoram Reich
10:00 - 11:00	**Basic course:** DT History & Traditions	The simonian tradition in design (Economics, info, learning, decision, problem solving tradition)	Eswaran Subrahmanian
11:00 - 11:30	**Break**		
11:30 - 12:30	**Basic course:** DT History & Traditions	Machine/technical system tradition (German systematic)	Sandor Vajna
12:30 - 14:00	**Lunch**		
14:00 - 15:00	**Basic course:** DT History & Traditions	Artistic tradition in design: history and theoretical interpretation	Armand Hatchuel
15:00 - 16:00	**Basic course:** Challenges of DT research	Old problems and contemporary issues	Pascal Le Masson & Benoit Weil
16:00 - 16:30	**Break**		
16:30 - 17:15	**Advanced course 1**	Biomimetics with design theory	Jacquelyn K.S. Nagel
17:15 - 18:00	**Advanced course 1**	Enhanced parameter analysis method	Ehud Kroll

Day 2: Salle Vendôme

Day 2 - 1st Fev 2018			
Timetable	**Type of Course**	**Title Course**	**Speakers**
9:00 - 10:00	**Basic course:** Generativity	Generativity & robustness in design: from GDT to C-K	Armand Hatchuel
10:00 - 11:00	**Basic course:** Knowledge structures I	Knowledge structure in design (n-dim, category theory, matroïd, sp splitting condition)	Eswaran Subrahmanian
11:00 - 11:30	**Break**		
11:30 - 12:30	**Basic course:** Knowledge structures II	Generative artificial intelligence	Akin Kazakci
12:30 - 14:00	**Lunch**		
14:00 - 14:45	**Advanced course 2**	Alternative interpretations of C-K theory in maths	Armand Hatchuel
14:45 - 15:30	**Advanced course 2**	Progress in axiomatic design	Christopher Brown
15:30 - 16:00	**Break**		
16:00 - 17:30	**Master class 1**		Benjamin Cabanes + Professorial College

Day 3: Amphi Schlumberger – V107

Day 3 - 2nd Fev 2018			
Timetable	**Type of Course**	**Title Course**	**Speakers**
9:00 - 10:00	**Basic course:** Social spaces	An introduction to the PSI (Product - Social – Institutional) Framework	Yoram Reich
10:00 - 11:00	**Master Class 2**		Benjamin Cabanes + Professorial College
11:00 - 11:30	**Break**		
11:30 - 12:30	**Master Class 2**		Benjamin Cabanes + Professorial College
12:30 - 14:00	**Lunch**		
14:00 - 14:45	**Advanced course 3**	Rethinking knowledge management based on design theory	Benjamin Cabanes
14:45 - 15:30	**Publishing in design theory**		Yoram Reich
15:30 - 16:00	**Break**		
16:00 - 17:30	**Publishing in design theory**		Yoram Reich
18:00 - 19:30	**Cocktail**		

Design theory Special Interest Group

The general goal of the Design theory SIG is to organize, collect and support research work that contributes to the renewal of Design theory by benefiting from new scientific advances, and by adapting it to highly innovative design situations.
The SIG evolves along two main directions: the "hard program" (formal design theory) and the "open program" (design theory and design issues), that are closely interacting with each other: the "open program" uses the results of the hard program to deal with issues in many areas (including management, economics, art and, philosophy). This interaction has also lead to raise new questions for the "hard program". This dual logic was used for instance to discuss design theory and methods (how methods use DT and imploring DT to ask new questions to enhance itself) or to discuss design enigma coming from art (how art and symbolic objects could raise interesting questions for DT).
The work has been divided into four axes:

1. ***Design theory, Mathematics and formalized models***

The SIG relies now on a large set of formalized theories and models. In the recent years the SIG has explored the mathematical foundations of design theory (forcing, splitting condition, category theory and Topos), design and possibility theory, design and constructivism, design and logic, design and matroid, generative functions, design and machine learning, design and algebraic extensions, design and generative data science, design and models of generative knowledge structures.

2. ***Design theory and new approaches of flexible structures of knowledge***

This second topic studies the relationship between, flexible knowledge structures and design theory. It developed through an elaboration of the concept of the interdisciplinary engineering knowledge genome as well as continuous work on n-dim and flat spaces as potential structures for design.
Several works discussed the relationship between design and specific "non-verbal" types of knowledge such as emotion, sensations, music, drawing…
Models of the generativity of knowledge structure have been presented and discussed (Topos structure and design, generativity of "patrimoine de creation", autogenetic design theory, generativity in deep learning).

3. ***Theory-driven experiments**:*

This third axis includes fundamentals from neuroscience, with discussion of design fixation and inhibitory control in the human brain.
Along this line of exploration many innovative design experiments were reported. Studies were reported on the use of design methods derived from design theory. In particular: works on KCP method and its improvement, and, on the use of design methods in different cultures
Experiments on "design of gestures", and "design thinking" were also reported. In particular researchers are today improving techniques to measure the generativity of design methods such as "design thinking".

4. ***History of Design theories, contemporary context and identity of objects:***

Building on the work on the history of design theory in several perspectives (Bauhaus, Gracian rhetoric, German systematic and, others), a new dimension of explorations led to the new theme "new critic in design and the identity of objects".
The SIG dedicated several sessions and works to learn more and diffuse the Theory of Technical System of Hubka and Eder and on the Autogenetic Design Theory.

Chairmen: Pascal Le Masson, Eswaran Subrahmanian;
Secretary : Akin Kazakçi
Founding chairmen : Armand Hatchuel, Yoram Reich
URL website: http://tmci.mines-paristech.fr/design-theory/

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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]

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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

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 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,

[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.

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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 startups, 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.

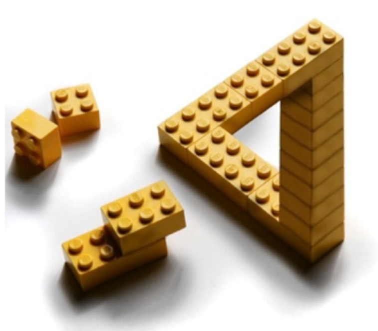

Fig. 1 Escher Lego—Erik Johansson

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).

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

[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).

[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

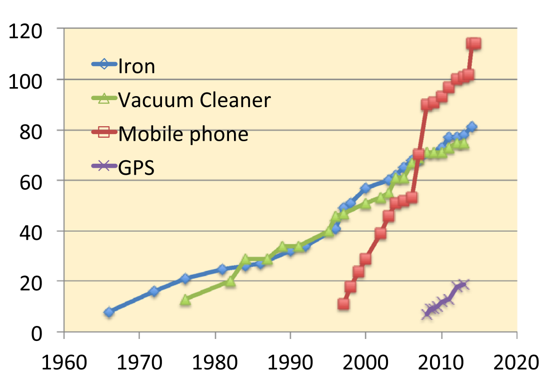

Fig. 2 Cumulative number of new functional characteristics that a product type acquires over time, for 4 types of products, based on the data from the archives of French Consumer Report "Que Choisir" (Source: El Qaoumi et al. 2017)

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.

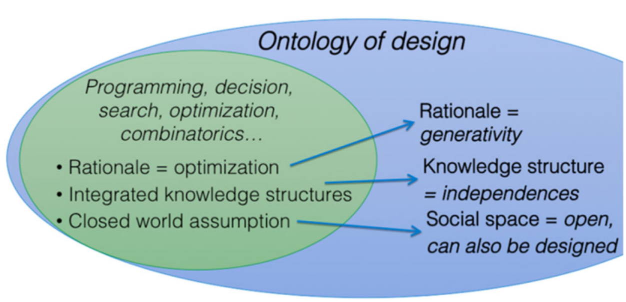

Fig. 3 The ontology of design as an extension of the ontology of decision-optimization

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?

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[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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