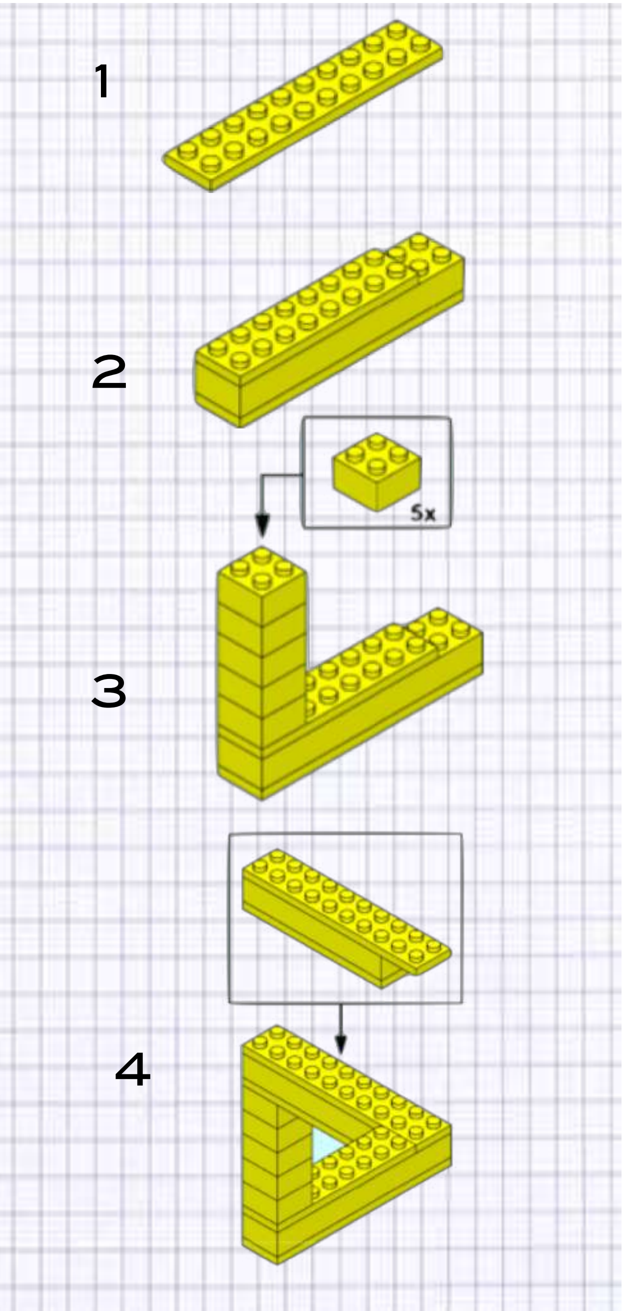
4TH TUTORIAL OF THE DESIGN THEORY SIG

29TH JAN – 31ST FEB, 2020 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

MASTER CLASS & PUBLISHING IN DESIGN THEORY

MINES ParisTech
60 boulevard Saint Michel Paris 75006, France
http://designtheory.sciencesconf.org/

design theory and methods for innovation

institut interdisciplinaire de l'innovation

MINES ParisTech

PSL

4th SIG Design Theory Tutorial (29-30-31 jan 2020, Paris, France)

Professorial college:

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
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
Camarda Anaëlle	MINES ParisTech	France, Paris
Fritzsche Albrecht	Ulm University	Germany, Ulm
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
Pollard Blake	NIST	USA, Gaithersburg
Reich Yoram	Tel Aviv University	Israel, Tel Aviv
Smulders Frido	TU Delft	Deflt, Netherlands
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: 7 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, phd dissertation, publication projects
- 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.
- One session on "publishing in design theory"

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

Basic Course	Advanced Topic / Paper Discussion	Publication discussion & Master Class

Day 1 – 29 Jan 2019			
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
10:00 - 11:00	**Basic course:** Classical School	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:** Classical School	An overview on the Design Methodology by Gerhard Pahl and Wolfgang Beitz	Sandor Vajna
12:30 - 14:00	**Lunch**		
14:00 - 15:00	**Basic course:** Contemporary Formal Models I	Introduction to CK Design Theory	Pascal Le Masson & Benoit Weil
15:00 - 16:00	**Conference**	Design theory and the art tradition	Armand Hatchuel
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	**Conference**	CK Practice using the Nobel C 60 molecul	Thomas Zung

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

Day 2 - 30 Jan 2019			
Timetable	**Type of Course**	**Title Course**	**Speakers**
9:00 - 10:00	**Basic course:** Contemporary Formal Models II	Knowledge structure in design (n-dim, category theory, matroïd, sp splitting condition)	Eswaran Subrahmanian & Blake Pollard
10:00 - 11:00	**Basic course:** Contemporary Formal Models III	Enhanced parameter analysis method	Ehud Kroll
11:00 - 11:30	**Break**		
11:30 - 12:30	**Basic course:** Contemporary Formal Models IV	An introduction to the PSI (Product - Social – Institutional) Framework	Yoram Reich
12:30 - 14:00	**Lunch**		
14:00 – 15:00	**Master class 1**		Professorial College
15:00 – 16:00	**Advanced topic / Paper discussion (2)**	Biomimetics with design theory (Vendôme classroom, visioconf)	Jacquelyn K.S. Nagel
16:00 - 16:30	**Break**		
16:30 - 17:30	**Advanced topic / Paper discussion (3)**	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 – 31 Jan 2019			
Timetable	**Type of Course**	**Title Course**	**Speakers**
9:00 - 9:45	**Advanced topic / Paper discussion (4)**	Demonstration of fixation effect during generation of creative ideas from fundamental experimentation approach to applied experimentations.	Anaëlle Camarda
9:45 - 10:30	**Advanced topic / Paper discussion (5)**	Generative artificial intelligence	Pascal Le Masson
10:30 - 11:00	**Break**		
11:00 – 11:45	**Advanced topic / Paper discussion (6)**	Conjunctions of Design and Automated Search in Digital Innovation	Albrecht Fritzsche
11:45 - 12:30	**Master Class 2**		Professorial College
12:30 - 14:00	**Lunch**		
14:00 – 15:00	**Master Class 3**		Professorial College
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	Publication discussion & Master Class

Day 1 – 29 Jan 2019			
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
10:00 - 11:00	**Basic course:** Classical School	The simonian tradition in design (Economics, info, learning, decision, problem solving tradition)	Eswaran Subrahmanian
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Pascal LE MASSON

Professor at MINES ParisTech –PSL Research University
Chair of Design Theory and Methods for Innovation
Deputy director of the Centre of Management Science – i3 UMR CNRS 9217
Chairman of the Design Theory SIG of the Design Society (with Eswaran Subrahmanian)
Chairman of the Innovation SIG of the European Academy of Management

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.

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ORIGINAL PAPER

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

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Received: 27 October 2017 / Revised: 28 October 2017 / Accepted: 30 October 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 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

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[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

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[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.

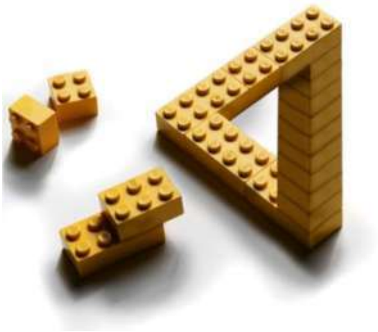

Fig. 1 Escher Lego—Erik Johansson

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

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[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.

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[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

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[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

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[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 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).

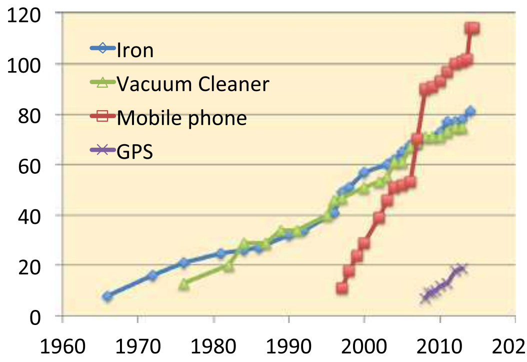

Fig. 2 Cumulative number of new functional characteristics that a product type acquires over time, for 4 types of products, based on the data from the archives of French Consumer Report "Que Choisir" (Source: El Qaoumi et al. 2017)

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.

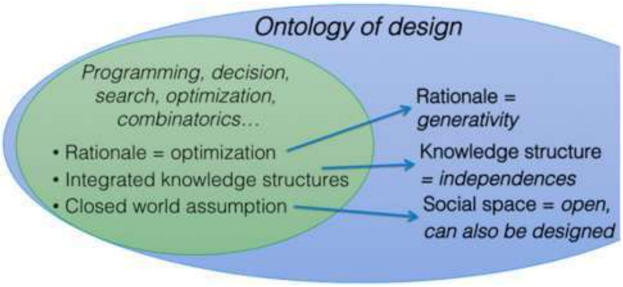

Fig. 3 The ontology of design as an extension of the ontology of decision-optimization

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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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.

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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 <u>well-defined</u>.

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 <u>ill-defined</u>.

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 <u>Plans and the Structure of Behavior</u> or in Walter Reitman*s <u>Cognition and Thought</u>[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

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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 have 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 analyzed5,

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 report6. 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).

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* 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.

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

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

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

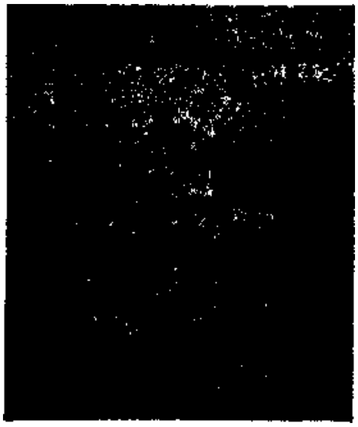


FIGURE I

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 C1. ("Sink wastes space" is never utilized.) Given C4. 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. ("Other bath" never utilized.) Retrieves C13 from memory. <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. [C1] Identifies DU12. Removes DU12. 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. C4 ~ DU6 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** **C15 ~ C4** **<C4 ~ DU6c>** **DU6 ∈ DU4** **Identifies DU3.** **[C1]** **Mentions processing strategy.** **C19 x (?) Locates DU4.** **Identifies DU12.** **Location of DU6 ~ C17.** **C17x.** **<u>STARTS ALTERNATIVE ONE</u>**
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.** **Identifies DU2.**

Figure Ha

maintain the two sinks. It seems that they are accepted. They just don't like the arrangement.	[C3]
<u>PM7</u> 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 <u>Graphic Standards</u>'.) I'm interested in spaces between, say, sink and a wall. ('Those are in Graphic Standards.)	[C4] [DU6] (Same question that is asked in PM36.)
<u>PM8</u> Oh, okay. Let's see. (Looks in <u>Graphic Standards</u>.) 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. Locates DU5. Identifies C18, [C18*location of DU5.]
<u>PM9</u> 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. [C18] <C18 ~ DU8>
<u>PM10</u> ('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] **<C11 x (Removes DU2).>** C19 x DU4 "I prefer storage beneath window". Identifies C20. [C20*location of DU4.]
<u>PM11</u> 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.) Locates DU4. No room for DU5.

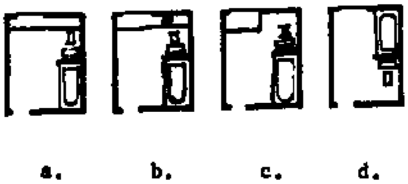


Figure IIb

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> STARTS ALTERNATIVE TWO <C2 ~ C21> 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. Measures tub to far wall.
PM13 That's three foot six across...Would the window have to stay where it is? (^{f}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. C22*location of DU4. 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. <C19*location of DU4.> 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.> C14 and C23*location of DU10.(?) 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.> Identifies C25.> [C24 and C25* location of DU13.] <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 [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] [C22 x] [C20 x] [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. [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. 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] No DU8. [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 necessary 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. **Identifies** C34. C34 ~ DU6c. [Locates DU6c.] Locates DU6c. [DU1] 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'.) I was thinking of going to another possibility of putting the tub

DU3. Wall = tub = 4 inches.
Locates DU10.
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
DU3.
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",
GOES ON TO ALTERNATIVE THREE
Locates DU3.
GOES TO ORIGINAL SOLUTION
C21 xoriginal sol. "fairly efficient".
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 countertop for a bathroom is 22" deep.')

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".
GOES TO ALTERNATIVE THREE
C21*location of DU2.
[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.]
Locates mirror. (Joke).
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.
Retrieves C27 from memory.
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	
<u>PM31</u> 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 <u>Graphic Standards</u>.)... 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 C10.
<u>PM32</u> 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 = C10x. Locates DU2. C14 x "don't go along with". ABANDONS ALTERNATIVE THREE
<u>PM33</u> 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.	[C1] **<u>REVIEWS FIRST ALTERNATIVE</u>** **<C1 ~ DU3b>** **Identifies DU3b.C2 x.** **Locates DU3b.** **C14 ~ DU12** **C14*location of DU12.**
<u>PM34</u> ('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." STARTS ALTERNATIVE FOUR (Same as alternative one) [C2.] [Orig. solution] DU1. 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. BEGINS ALTERNATIVE FIVE identifies C29.> C28 and C29*location of DU4. Reads CII.
PM37 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. Locates DU4 & DU5. C33*location of DU6. Locates DU1. 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. [C28] [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, REJECTS ALTERNATIVE FIVE RETURNS TO ALTERNATIVE FOUR

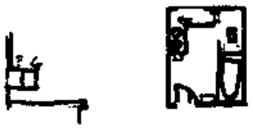
Figure IIg

PM40 I like the bathtub and watercloset 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] Locates DU1 and DU4. C4 x. 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] C26 x"wasted space here". C7 and C33*location of DU5. 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". [C3] [C8] [Locates DU3b] 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. <DU5 = DU6 = DU5.> 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. C2 x DU7a "too expensive". Identifies DU7b <C2x(DU7a=DU7b). USES ANOTHER REPRESENTATION Locates DU7b. Retrieves C30 from memory. 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 everyday. 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 .

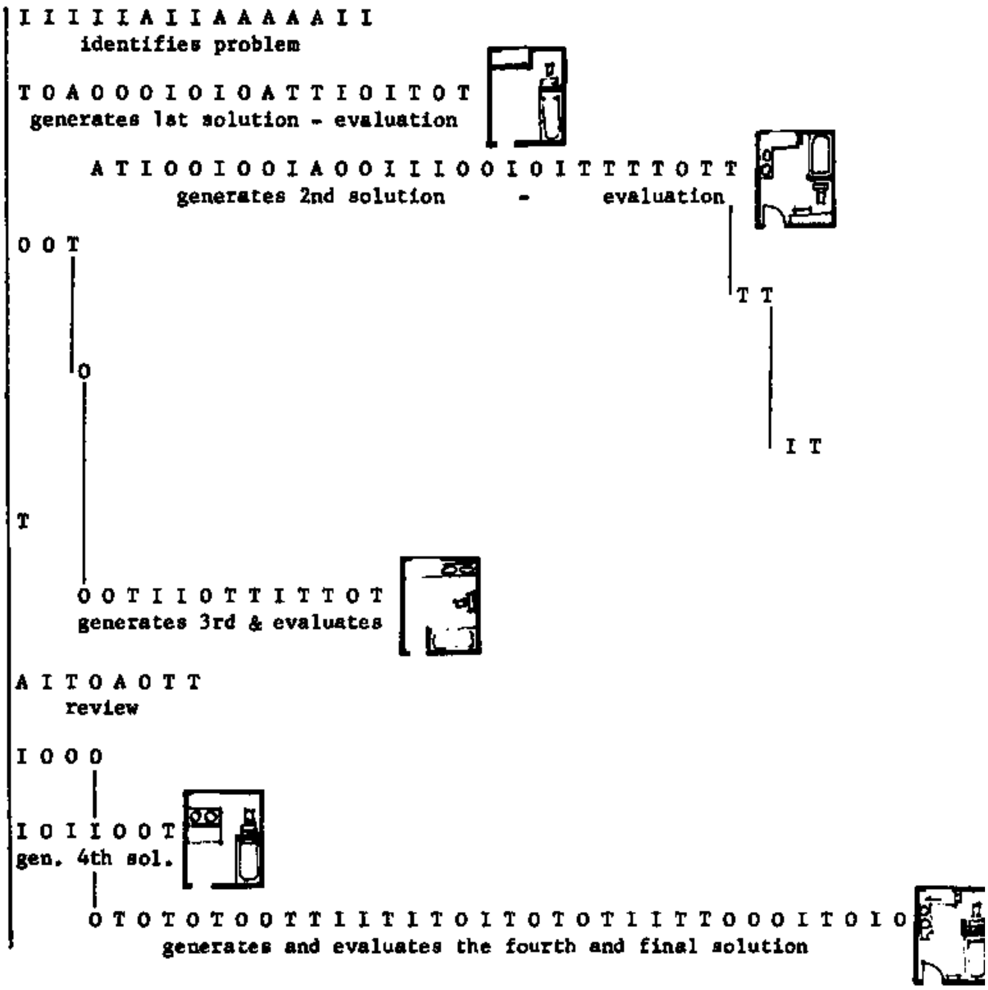


Figure III. Schematic behavior graph of processing carried out by the S. Time is in the direction of across the graph then down. Processing which begins with a partial solution or cycles between two solutions can be identified. Each symbol represents a transformation.

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.

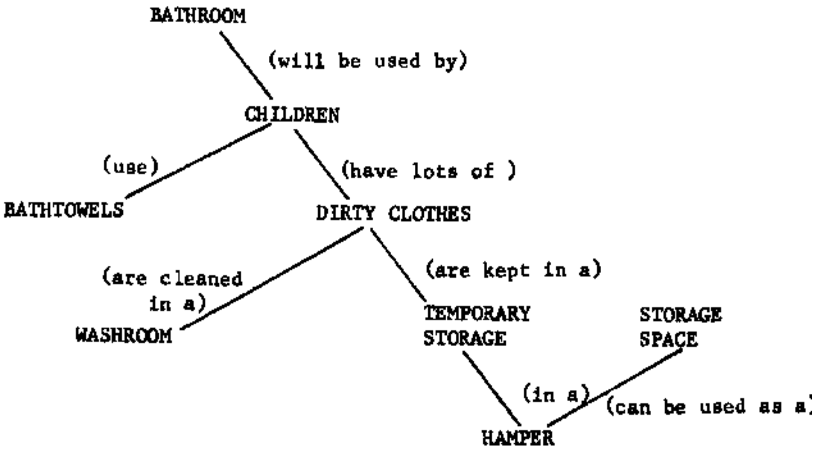


Figure VIa

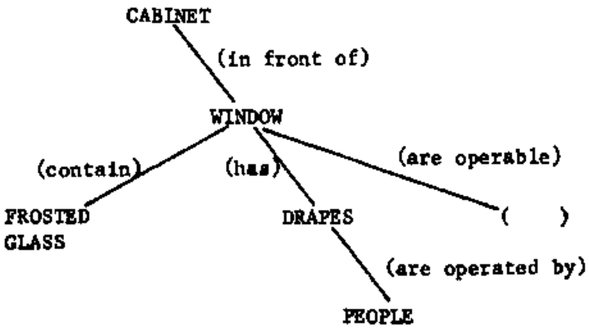


Figure VIb. These two diagrams record the sequential retrieval of information. Time generally is in the direction from top to bottom.

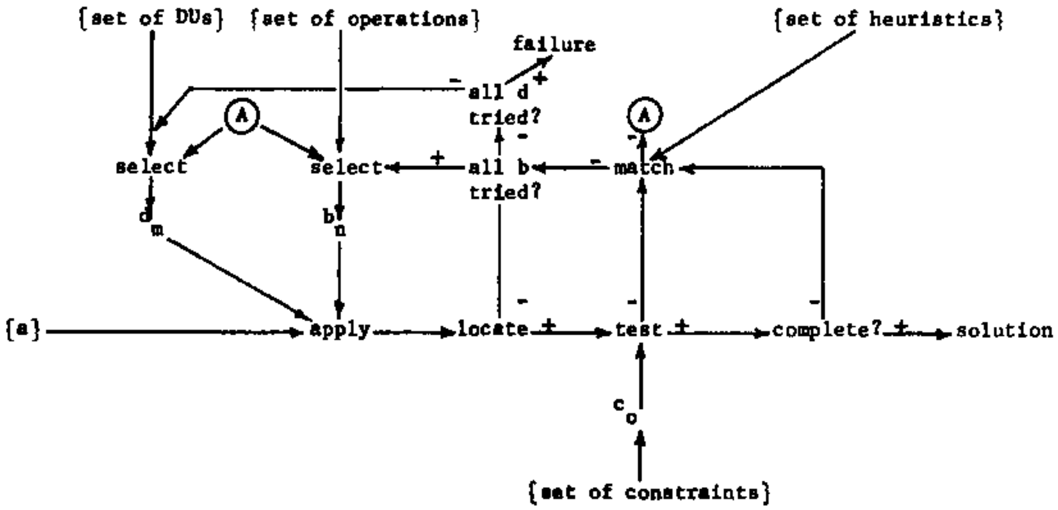


Figure VII. A schematic flowchart of the search aspect of space planning problems.

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

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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 :

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[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

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[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

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[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

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[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*

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[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

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[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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Sándor Vajna received his Doctor Engineer's degree from Karlsruhe University in 1982. After 12 years in industry in research & development, management, and consulting on Product Development, Design Methodology, CAx, and PLM, Vajna was promoted 1994 to Full Professor of the Chair of Information Technologies in Mechanical Engineering at the Otto-von-Guericke University Magdeburg, from which he retired on September 30, 2017. He was awarded prices from international institutions.
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Title of the Presentation:

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Synopsis:

Presentation of the genesis and of the main content of the Pahl / Beitz Method, its influence on German design research and on VDI guidelines (VDI = Verein Deutscher Ingenieure, German Association of Engineers). Outlook to actual research in order to adapt this method to current requirements.

Main References/ Further readings:

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ACHIEVING SIMPLICITY: A CONSIDERATION OF A SYSTEMATIC APPROACH

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ABSTRACT

Increasing demands on today's products as well as the opportunities offered by globalization and digitization are leading to the growth of ever more complex products. However, design principles from the field of design engineering require that a product be designed as unambiguous, safe and simple as possible. While "”unambiguous" and "”safe" are precisely defined and delimitable design principles, simplicity is a vague term. It is not possible to describe it completely with objective parameters. Simplicity results on the one hand from an objective product-relevant side, on the other hand from the experience and knowledge of the observer. Thus, a product that is perceived as simple by one person may seem complicated to another. From this the questions arise, with which attributes simplicity can be described, how these are to be captured and above all, how suitable recommendations for action for the developer are to be derived from it. In this paper, we present a concept for the analysis and evaluation of simplicity and the resulting recommendations for action. In this paper, an evaluation system for the subjective attributes of simplicity is created using the fuzzy sets approach. The result is discussed using a product example.

Keywords: Simplicity, Fuzzy, Decision-model, User-Centered Design

1. INTRODUCTION

Due to the ever-increasing variety of products, functional integration within a product, and an increasing flood of information, a reduction of the resulting complexity is required almost everywhere. The aim of all developments is to utilize the possibilities of technical systems in order to enable people to overcome performance limits or to maintain or expand their capabilities. Design principles from the field of design engineering demand that a product shall be as simple as possible. When developing products, the product has to be unambiguous, simple and safe. While “safety” and “unambiguity” can be defined in relation to a certain environment by precise definitions, simplicity is usually characterized by fuzzy parameters. Current approaches to the evaluation of simplicity consist either in the reduction to deterministic values [1], which gives the evaluation model a strong abstraction from the real model, or in the use of unclear parameters, which divide the fuzzy term simplicity into further fuzzy terms (e.g. a simple assembly results from an easy assembly) [2]. The first research question arises to what extent simplicity can be captured as subjective product characteristics and which methods serve as suitable tools for this purpose. The second research question deals with the extent to which suitable methods for simplifying a product can be made available systematically and situatively to the developer in this vague environment. The resulting paradigm shift inevitably leads to a change in conventional product development, as it leads to a need of adapted strategies and methods.

In this paper, we present a new concept for evaluating product simplicity. First, we give an overview of the definition of a simple product, to what extent different groups are to be considered, and which advantages simple products have. We discuss the individual attributes of simple products and their influence on each other. Based on this, the principle of fuzzy sets is described as a possible evaluation method for subjective attributes and explained within an example. We evaluate a simplicity index with the help of deterministic and fuzzy evaluation procedures. With this index, it is possible to divide the simplicity into different product categories.

2. DEMAND OF SIMPLE PRODUCTS

The first question that must be answered in this context is how the simplicity of a product is defined. A common definition of simplicity is often described by its relation to complicatedness and complexity. This has its origin in system theory [1], which defines a complicated system by the degree of diversity of the elements, their number and their interconnections. It is possible to simplify a complicated system by structuring and clustering. Thus, a complicated system can consist of a multitude of subsystems, which may be interpreted either as complicated or simple. The understanding of a complicated system depends on both experience and knowledge of the person, who interacts with the product. This is mostly not comprehensible for the non-expert, but can be taught. An example of this can be the acquisition of a driving license [3].

Complex systems also have a multitude of elements and connections between them. In addition, they are subject to seemingly random, dynamic changes that fluctuate over time. They are difficult to disassemble, calculate and organize [4]. By further exploring simplicity within product development, it is possible to identify a much larger number of research areas dealing with this topic (for further information of the selected authors refer to [4]).

TABLE 1: Research areas of interest [4]

Research area	Core subject	Selected authors
Engineering Design	Structural complexity: Simplicity result from the number of elements, the relationships between elements and their boundary conditions	(Pahl et al., 2013) (Ehrlenspiel und (Meerkamm, 2013) (Hubka, 1984)
Product Design	Variety of individual design elements influences the perception of simplicity and complexity	(Zeh, 2010) (Schneider, 2005) (Seeger, 2005)
Manufacturing	Lean production: employee training, customer involvement, low hierarchies	(Dombrowski and Mielke, 2015)
Assembly Design	Standardization, fragmentation and modularization simplify assembly	(Womack et al., 1992)
Maintenance	Disassembly, Assembly structure, Types of connection	(Pahl et al., 2013) (Ehrlenspiel und (Meerkamm, 2013)
Usability	Type of function execution, Effectiveness of execution, Efficiency of execution, Satisfaction of execution	(Robier, 2015), (Geis et al., 2015), (Choi and Lee, 2012)
User Experience	Types of product perception.	(Preim, 2010),

	Interplay of expectation conformity and the mental model. Ease of Use.	(Norman, 2013), (Quirmbach, 2013)
Management	Structural shift, Insufficient transparency, Product expansions, Complexity as know-how protection	(Olbrich and Battenfeld, 2005)
General Simplification	The ten laws of simplicity, Life simplification	(Maeda, 2007)

The analysis of the different research areas in Table 1 shows that a simple product is defined differently depending on the respective research area. While in system theory a system is defined as simple because of the number of its components and the number of relationships between them, the usability of products is mainly evaluated by the quality of the user interface. The focus here is on the efficient handling of the products together with the respective product design [5]. From the provider's point of view, both the producibility and the cost-effectiveness of the product is in the focus [6]. It can be concluded from this investigation that different approaches are pursued in achieving simplicity within the product life cycle (according to [7]), especially in distinguishing between the development process, i.e. the consideration of the provider (which covers developer, manufacturer, manager, salesperson etc.) and of the user (which covers the buyer as well). From the user's viewpoint a product is simple if the expected product benefits are available within a defined or rather expected time interval in an obvious and trouble-free manner, and in which the product exhibits the expected range of functions. From the provider's point of view, a product can also appear to be simple if its profitability can be achieved quickly as expected, and without disturbances [4].

In this paper, we will distinguish between these two user groups in describing simplicity. Additional, complicatedness is regarded as a precursor of complexity, which can be counteracted by appropriate human centricity. In addition to considering what constitutes a simple product, it should also be noted why a systematic development of simple products is desirable. Achieving simplicity offers several advantages for the user when dealing with products, processes, and services [8]:

- Quick and better understanding of the product context, resulting in a fast learning of the usage of the product.
- Reducing the chance of operating errors to increase user satisfaction.
- A faster purchase decision for simple services and products.
- A higher user acceptance.

In addition to these user-specific advantages, which of course also make themselves felt in the sales of the product, simple products offer advantages that benefit the provider [1]:

- Development and implementation of a simple product are influenced positively by simple processes and thus achieve results faster.
- Reduced assembly effort due to simplified shapes.
- Better comprehensibility due to simplified working principles and functional structures.
- Functional principles as well as simple forms support the predictability of both product performance and behavior.

In summary it can be concluded that, despite the many advantages of simple products, no uniform definition of a simple product prevails. On the one side this can be due to a narrow view on one's own field of research, on the other side to a mutual contradiction of the properties of simple products [4].

3. ATTRIBUTES OF SIMPLE PRODUCTS

The different approaches to simple products shown in Table1 illustrate that simplicity has a certain diversity in terms of definition and development. From this aspect of the diversity of simplicity, it is questionable which characteristics can be used to evaluate product simplicity. To this end, opinions and assessments of experts from research and industry on the subject of simple products were questioned in a workshop during the DESIGN 2018 Conference in Dubrovnik/Croatia. The aim was to determine the causes and characteristics for a simple product using a selection of previously prepared mechanical and mechatronic products. A distinction between user and provider view was defined in advance. To simplify the evaluation, the 55 collected characteristics were used within predefined attributes based on the attributes of Integrated Design Engineering (IDE) [6]. The attributes describe characteristics, properties, and features of a product throughout the entire product life cycle. A distinction must be made between the product attributes, which are defined directly by the product, the so-called fulfillment attributes that make statements about the quality of product performance and behavior, and the benefit attributes, which define the ideal and material capabilities of the product. To simplify the product properties, four attributes have been defined for both the users and providers point of view, as shown in the following figure.

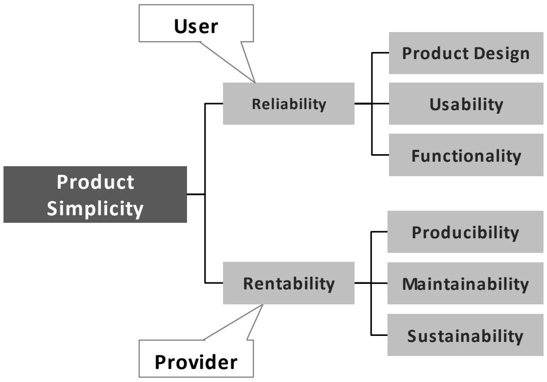


FIGURE 1: Attributes of simple products

The attributes of simple products are defined as follows, based on Vajna [9]:

- Product gestalt covers product culture, identity, and presence. It reflects the visual and emotional characteristics of the product and thus presents ("promises") both the product capability and the performance behavior to the user.
- Usability describes in a broader sense the performance, use and quality of the interface. It is characterized by efficiency, effectiveness and satisfaction of the user.
- Functionality describes the ability of the product to meet a set of discrete requirements. A distinction must be made between type, level and quality of a function, and the mutual influences between the functions of a product.
- Reliability is a fulfillment attribute that is defined by the resulting quality of the product. It is characterized by expected conformity of product performance, behavior, robustness (especially a minimum of operating errors and trouble shooting) and a long service life. As reliability covers the overall performance of the product, it is superior to the attributes (but this is not a statement for the weighting of the attributes).

When considering the provider's side, the focus is primarily on the entire product life cycle:

- Producibility provides all information necessary for the production of the product. It is a cost-oriented attribute. It defines under which logistical, technical and organizational conditions a product can be generated.
- Maintainability describes the ease with which a product can be maintained, adapted, or subjected to a new environment.
- Sustainability presents the ethical, ecological, and economical behavior of the product during its complete life cycle in a global environment, for which it defines the ecological requirements.
- Profitability defines the economic aspects from the provider's point of view. It is the primary reason for new developments. Like reliability, profitability results from the overall product performance and behavior.

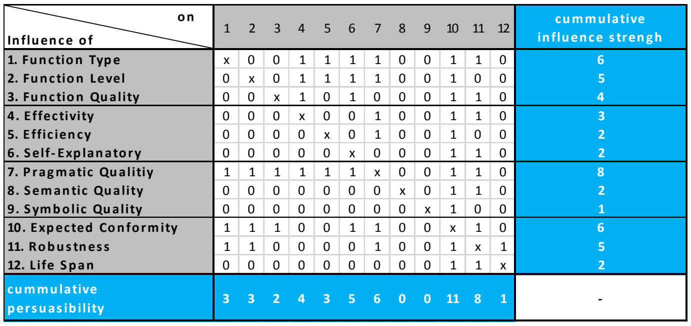
According to Vajna [9], the attributes are equivalent, so no attribute dominates an other. Since for product simplicity only a targeted selection of the attributes is considered, it is nevertheless useful to identify dominant influencers in order to create a weighting.

With the help of a dependency diagram, shown in Figure 2, it is possible to identify dominant dependencies nodes. In order to increase the level of detail, the attributes are subdivided into subcategories, based on the definitions of the attributes according to Vajna, and each is evaluated according to its impact. In a first step, all subcategories were examined for their dependencies. For a better understanding, the method will be shown based on the group of the user. The relationships of the provider's view are analyzed in the same way.

FIGURE 2: Dependency diagram of the user's viewpoint

It can be noted that the expected conformity is the most dependent. This is therefore not surprising, since on the one hand it belongs to the attribute of reliability, which is superior to the other as fulfillment attribute, and on the other hand expected conformity can be understood as result of the usage and is thus formed in the order of use after the other attributes. Further dependency nodes can be found in the pragmatic qualities (according to [10]) and the self-explanatory (according to the affordance in [11]). However, this analysis does not give any information about the dominance of the attributes among each other and thus also no information about the influence strength/persuasibility.

The influence matrix (also called paper computer) according to Vester [12] offers the possibility to analyze not only the variables with the greatest influence, but also the variables with the greatest power of persuasion. The principle of the Design Structure Matrix (DMS) is used to analyze the interaction in a system. The influence of each category on each other is examined and evaluated. The results are shown in Figure 3.



on Influence of	1	2	3	4	5	6	7	8	9	10	11	12	cummulative influence strengh
1. Function Type	x	0	0	1	1	1	1	0	0	1	1	0	6
2. Function Level	0	x	0	1	1	1	1	0	0	1	0	0	5
3. Function Quality	0	0	x	1	0	1	0	0	0	1	1	0	4
4. Effectivity	0	0	0	x	0	0	1	0	0	1	1	0	3
5. Efficiency	0	0	0	0	x	0	1	0	0	1	0	0	2
6. Self-Explanatory	0	0	0	0	0	x	0	0	0	1	1	0	2
7. Pragmatic Qualitiy	1	1	1	1	1	1	x	0	0	1	1	0	8
8. Semantic Quality	0	0	0	0	0	0	0	x	0	1	1	0	2
9. Symbolic Quality	0	0	0	0	0	0	0	0	x	1	0	0	1
10. Expected Conformity	1	1	1	0	0	1	1	0	0	x	1	0	6
11. Robustness	1	1	0	0	0	0	1	0	0	1	x	1	5
12. Life Span	0	0	0	0	0	0	0	0	0	1	1	x	2
cummulative persuasibility	3	3	2	4	3	5	6	0	0	11	8	1	-

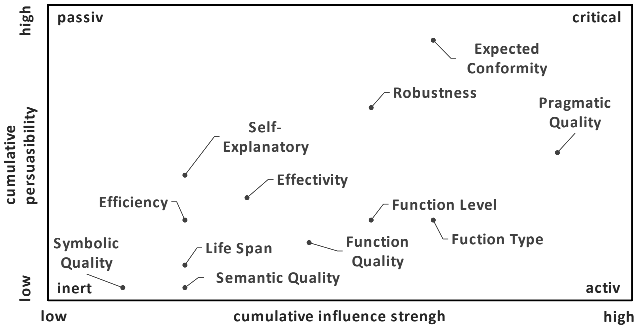


FIGURE 3: Dependency diagram of the user's viewpoint

It is obvious that above all pragmatic qualities of the product have a high influence on the other categories. This can be explained by the fact that the pragmatic qualities are decisively responsible for the expectation conformity, efficiency, effectiveness, and self-explanatory. At the same time, they are strongly influenced by the functionality, i.e. the type, degree and quality of a function and its interdependencies with the other product functions. It can also be concluded that robustness, service life, semantic and symbol qualities are very inert. They are little influenced, which can be explained by the fact that aesthetics, as a property of semantic qualities, has very little influence on the perception of simplicity [13]. At the same time, their influence on other categories is very weak, resulting in the low strength of influence. This leads to the conclusion that their impact on a simple product is low. This is also consistent with the results in Figure 2, in which especially the service life, as well as the semantic and symbolic qualities, have little impact.

From the provider's point of view, it can be seen that, similar to Hartmann [1], simplicity can be evaluated using system theory. The number of elements and relationships is decisive for the level of complexity of both design and assembly (and thus also for maintenance). The more different elements and relations exist between them, the more complex the production process will be. If a larger context than the single product is considered, the scope of product variants is also relevant for the provider. Here too, the product variety, which increases the combination of possible elements, leads to increased product complexity. This system-theoretical approach can be related not only to the number of components, but also to the diversity of manufacturing and assembly processes.

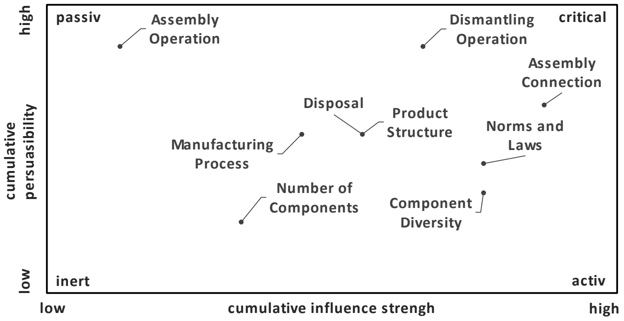


FIGURE 4: Dependency diagram of the provider's viewpoint

In addition, a mutual influence of the properties can be determined. On the one hand, a screw connection allows simple assembly and maintenance, while at the same time increases the design effort, the required installation space, and the number of production steps. On the other hand, an adhesive joint reduces these points, but results in a costly disassembly and difficult disposal.

In summary, simplicity can be described by the attributes of IDE. A distinction has to be made between the user view, which is described by a multitude of subjective and user-dependent variables, and the provider view, which can be defined by a system theoretical approach. Active and critical subcategories in particular should be given higher weighting, since their influence is stronger. The inert categories have the least influence and thus also the lowest weighting. Furthermore, the current subcategories must be checked for completeness. However, it is questionable whether further categories have to be included for the evaluation of simplicity.

4. FUZZY DECISIONS SYSTEMS

As mentioned in Section 1, the evaluation of simplicity is not possible solely through deterministic values. While the level of functionality or the life span can be described by sharp, deterministic values, attributes such as product gestalt and usability are mainly described by subjective and fuzzy values.

The quality of the self-explanation is not only possible through the visual characteristics of a product. Self-explanation results from the experience and knowledge of the user, the associations (mental models) that the design of the product wants to address and the actual mental model of the user possesses [11]. Usually, questions as to whether a product is self-explanatory or intuitive are answered with a linguistic evaluation, such as "good" or "bad". The valuation method of the Likert scale is often used to collect this information. In this, so-called items are evaluated within a given multi-level response scale with the help of fuzzy variables. It is very easy for people to give a linguistic assessment of a condition without setting clear boundaries. These evaluations are generally not based on a comprehensive theoretical knowledge, but on a summary of rules which the evaluator subconsciously follows in his decision [14]. It is questionable, however, how these fuzzy variables such as "beautiful" or "good" can be traced back to deterministic values. The aim is to establish a simplicity index, which includes both the objectively captured parameters and the user-dependent subjective ones. A comparison of the products to be evaluated requires a standardized form of all different value dimensions. Such standardization can be achieved by awarding points on a numerical scale of values, separated according to quantitative values and qualitative statements [15]. While from the provider's point of view the attributes contain quantitative values, the evaluation of the usage of products must be based on qualitative statements. It is questionable how clearly definable states can be derived from fuzzy evaluations of a Likert scale.

Fuzzy decision systems, which do not rely on such distinct limits within evaluation variables, offer a remedy [16]. Examples for the use of such fuzzy decision systems in linguistic environments can be found under [14, 17, 18]. In contrast to the classic quantity theory, in which a value can only be assigned to one set at a time, fuzzy sets can belong to more than one set by means of different affiliations. This means that a product can be considered simple to a certain extent and complex to another certain extent [15]. Figure 5 shows the process of such a fuzzy decision system [14].

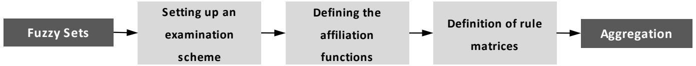


FIGURE 5: Structure of a fuzzy decision system [14]

The first step is to create an examination scheme, which subdivides the mostly abstract and fuzzy variables into more easily comprehensible categories. The aim is to obtain an overall evaluation by aggregating the individual parameters. The attributes and their categories listed in Section 3 can be understood as an example of such a subdivision. For further use, an affiliation function must be defined for each category. In contrast to the classic set definition, in which each element has a unique affiliation to a set, fuzzy elements can also only belong to a set to a certain degree [16]. These affiliation functions represent the value of a linguistic statement versus a deterministic value. To illustrate the principle, Figure 6 shows examples of the affiliation functions of the subcategories effectiveness, efficiency and self-explanation of the attribute usability.

Effectiveness and efficiency are defined in DIN EN ISO 9241-210 [19]. Effectiveness is both accuracy and completeness with which users achieve a particular goal. Efficiency is described as the effort, in relation to accuracy and completeness, with which the user achieves a particular goal. Self-explanation is defined by the frequency of operating errors during the use. For the sake of clarity, the linguistic evaluation options used in this paper have been limited to a maximum of three.

The affiliation functions are rules formulated by experts, which describe the circumstance of the assessment [14]. The affiliation functions shown in Figure 6 are the results of investigations of projects within the IDE master course at our university. Within these projects, a product is developed from product idea to prototype. These projects run in close cooperation with the industry. A big focus is on a user-centered development and thus offers a good approach to the creation of affiliation functions from the user's point of view.

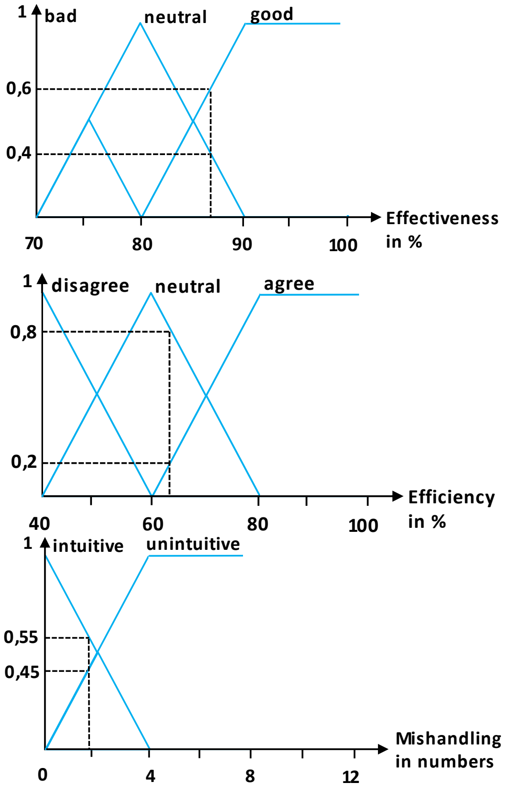


FIGURE 6: Dependency

The affiliation function defines the affiliation of a set of a linguistic formulation within a defined interval. The example of effectiveness shows that at least 80% of the expected target has been achieved if the effectiveness is "good". At the same time, however, they also belong to the group of those assessed as "neutral", but to a much lesser extent. 85% belong equally to 0.5 to the amount of neutral effectiveness and to 0.5 to the amount of good effectiveness.

In order to derive an overall statement about the usability from these rules, a rule matrix is necessary that interprets the individual evaluation options. This rule matrix varies in size depending on the number of possible answers and the number of areas examined due to the increasing combinatorial possibilities. The expert, who draws up the table of rules, or the team of experts must define the membership functions in such a way that they reflect his subjective perception correctly. As this is experience knowledge, one will have to be satisfied with an approximate description. This is also expressed in the fact that mostly simple functional forms are used and the same description pattern appears again [14]. In the example shown in Figure 6, a total of eighteen possible combinations result, which can arise as subset for usability, shown in Table 2.

TABLE 2: Rule matrix for usability evaluation

Effectiveness	**Efficiency**	**Self - Explanatory**	**Usability**
bad	disagree	unintuitive	very bad
bad	neutral	unintuitive	very bad
bad	agree	unintuitive	bad
bad	disagree	intuitive	bad
bad	neutral	intuitive	neutral
bad	agree	intuitive	neutral
neutral	disagree	unintuitive	very bad
neutral	neutral	unintuitive	bad ***(0,4; 0,8; 0,55) = 1,75 / 14,5%***
neutral	agree	unintuitive	neutral ***(0,4; 0,2; 0,55) = 1,15 / 9,5%***
neutral	disagree	intuitive	neutral
neutral	neutral	intuitive	neutral ***(0,4; 0,8; 0,45) = 1,65***
neutral	agree	intuitive	very good ***(0,4; 0,2; 0,45) = 1,05 / 13,7%***
good	disagree	unintuitive	bad
good	neutral	unintuitive	neutral ***(0,6; 0,8; 0,55) = 1,95 / 16,2%***
good	agree	unintuitive	good ***(0,6; 0,2; 0,55) = 1,35 / 11,2%***
good	disagree	intuitive	good
good	neutral	intuitive	very good ***(0,6; 0,8; 0,45) = 1,85 / 15,4%***
good	agree	intuitive	very good ***(0,6; 0,2; 0,45) = 1,25 / 10,4%***

If we assume, for example, that the effectiveness of a product is estimated at 87%, the efficiency at 64% and the self-explanation with the average number of operating errors at 2 (see Figure 6), then we have a total of 8 affiliations for the usability of the product. For the "very good" usability set, there is a good effectiveness of 0.6, a good effectiveness of 0.2 and an intuitive handling of 0.45. If the other affiliations are taken into account and standardized by their total sum, an aggregation is possible. This results in a bad usability of 14.5%, a neutral usability of 40%, a good usability of 11% and a very good usability of 34.5%. Figure 7 gives a graphical overview of the resulting conditions. It should be noted that these values are not probabilities of usability, but represent allocations to the various quantities.

In order to form a final aggregation of the affiliations, it makes sense to carry out a so-called defuzzification in the last step. By forming the centroid of the area, the distribution can be returned to a single value (represented by the dash-point line in Figure 7) [14].

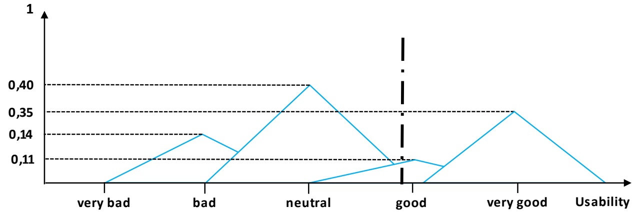


FIGURE 7: Aggregation of usability according to Table 2

If the scale from "very bad" to "very good" is assigned from zero to one, the result for usability after defuzzification is 0.73. In this example, no weighting of the categories was considered.

5. A CASE STUDY

In this section, we present two different coffee machines as an example the evaluation method for fuzzy sets . The two products were evaluated in a questionnaire on simple products. Twenty-seven students from the field of mechanical engineering took part in the evaluation. Functionality, usability, product gestalt and reliability were tested based on given technical data and image sections.

FIGURE 8: Products of the case-study [20, 21]

A total of seventeen items were provided for both products, which were evaluated on a scale of -2 to +2. The subcategories presented in Section 3 were further specified in some cases to make them easier for participants to understand. In particular, robustness is further subdivided into error susceptibility, maintenance ability and resource consumption. In addition, two items on familiarity have been added under the heading "Experience" to supplement the expectation conformity. An overview of all categories used as well as the presentation of the collected results of the questionnaire is shown in Figure 9.

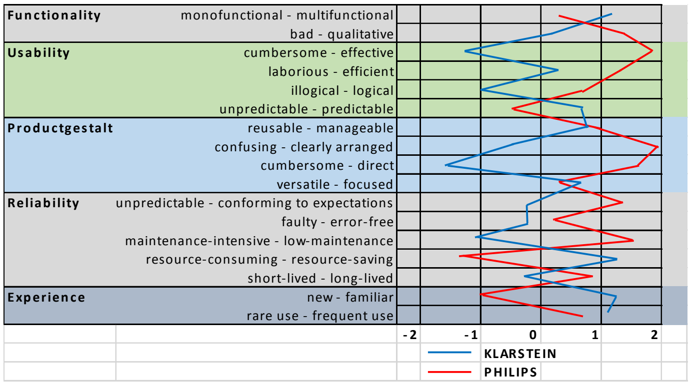


FIGURE 9: Items of the questionnaire

The fact that there are only two valuation parameters to choose from means that the resulting combinations of the rule matrix are kept as low as possible. Nevertheless, the rule matrix of reliability results from five items to be evaluated in 32 possible evaluation scenarios. Here it is recommended to evaluate robustness separately from expected conformity and life span in a first step. This sets the evaluation structure one level lower and only has to be evaluated with eight possible scenarios. The resulting distribution is then not subjected to any defuzzification, but is included in the next evaluation as new input for the next higher level. This is because each characteristic represents a possible state that occurs with the corresponding level of affiliation.

Each item was summarized via the affiliation functions and the respective rule matrix and mapped within the respective attributes. Figure 10 shows the assignment of the four subcategories for the first coffee machine.

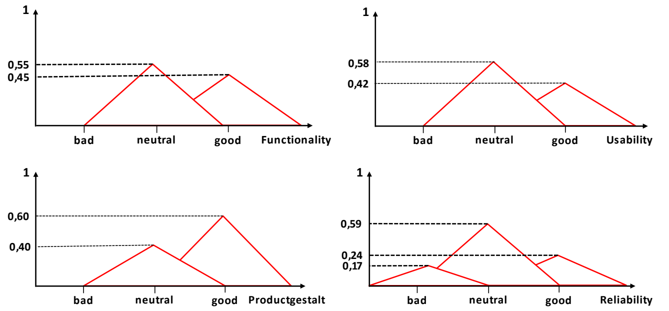


FIGURE 10: Aggregation of usability according to Table 2

It is evident that, with the exception of reliability, all evaluations are distributed in the neutral to good range. Only the reliability belongs to a subset of the bad evaluations, which can be attributed to the consumption of resources.

In the last step, these four attributes are aggregated and combined to form a simplicity index. The rule matrix included 81 possible affiliations, of which 24 are used for the first coffee machine due to the strong distribution between "neutral" and "good". Similar to Figure 7, a scale in five interval steps is selected. Four of the classifications are "simple", eight are "less simple" and twelve are "neutral". The largest set is arranged with a distribution of 0.5 in the “neutral” range, followed by “less simple” with 0.33 and “simple” with the affiliation of 0.17. The same procedure was followed for the evaluation of the second coffee machine. Due to the much broader distribution of the evaluated items, the result was more scattered, whereby a total of 36 of 81 rule sets were considered, which were summarized in five interval steps. Figure 11 shows the resulting aggregations for the two coffee machines.

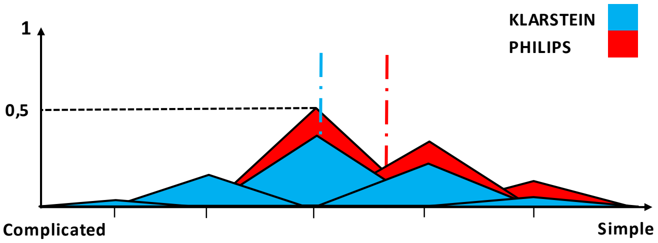


FIGURE 11: Aggregation of the simplicity-index

In contrast to the first coffee machine, the aggregation of the second machine is much more widely spread. The focus is also in the “neutral” range, but it is distributed over the whole interval. A defuzzification of the two evaluations with the help of the centroid of area in the last step results in a simplicity index of 0.69 for the first coffee machine and 0.51 for the second.

6. DISCUSSION

As shown in the case study, we were able to apply the principle of fuzzy quantities within the approach of a decision making system to evaluate simple products from the user's point of view. This approach makes it possible to convert the evaluation of fuzzy linguistic parameters into a deterministic indicator. The primary advantage here is the rule matrix. They can be used to define and aggregate complex relationships. While after use a person can give an assessment of the simplicity of the product without problems based on the properties of the product, it is mathematically difficult to understand which attributes of the product lead to this statement. It may be that the usability of the product had weaknesses, but this was compensated by both reliability and product gestalt, and thus the whole product is still perceived as simple. The rule matrix represents all possible combinations at different attribute quality levels and defines a resulting simplicity for each occurrence.

In addition, it is possible to integrate a weighting based on the dependencies from Section 3 within this evaluation. The weighting can be applied within the rule matrix. Thus, a good reliability of the product can be weighted higher than the usability, whereby simplicity is always assigned to the better interval in favour of reliability. On the other hand, a weighting can take place within the affiliation functions. For this a value system would be needed, which strengthens or diminishes the affiliations, depending on the attribute considered in each case.

The consistency of the current subcategories of the attributes from Section 3 should be viewed critically. Especially in the area of usability and product gestalt, a mixture within the self-explanatory and pragmatic functions can be observed. It is questionable to what extent a separation between usability and product gestalt can be defined. One approach is to evaluate the pragmatic functions for usability and thus to reduce the focus of the productgestalt to the aesthetic and semantic properties. Another problem is the number of combinatorial possibilities. If the simplicity is divided into four attributes with three categories each, which are divided into three evaluation items, there are twenty-seven different combinations per attribute on the first level. For summarizing the attributes, eighty-one different combinations are possible. Together with all four attributes, there are 189 required rules. If more evaluation items or more categories are used, the possible combinatorics quickly become unmanageable.

7. CONCLUSION AND OUTLOOK

In this paper we presented a concept for evaluating product simplicity. A list of the relevant areas influencing the introduction was created on the basis of a detailed literature review. From the resulting definition eight attributes of IDE were adopted, which were used as evaluation criteria. We combined these attributes with the evaluation approach of fuzzy quantities to create an simplicity index from the user's point of view. It turned out that particularly fuzzy sets provide a good insight into the cause-effect relationships within a evaluation system.

In the next steps a further verification of the affiliation functions will be necessary. Their quality has a decisive influence on the final result. It could also be interesting to apply the used principle on the provider's point of view. Thanks to the logical connections of the rule matrix, a comprehensible evaluation could also be made here.

Further research will be done on possible strategies and methods for simplifying a product. Thus, in addition to the simplicity index, suitable instructions for action could be evaluated and provided. Moreover, the evaluation in this post ignored the user's experience. It is questionable what influence the user's experience and knowledge have on the evaluation of the simplicity of a product.

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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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See references in "Chapter 4" above.

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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*,
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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).

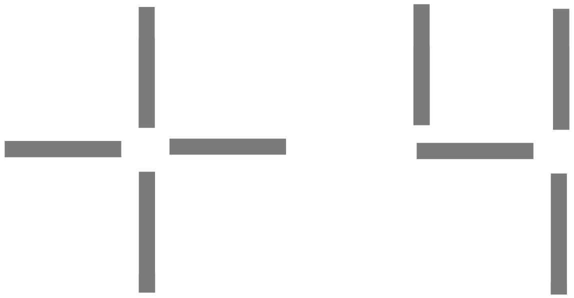

Fig. 4.1 An example of fixation. Form a square by moving just one of the matches in the left-hand figure. The problem seems insoluble as long as we think of the square as a geometric shape. The problem is solved by recalling that a square may also be the result of the mathematical operation of raising 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*

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[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* $p_1, p_2, \ldots p_k$ *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

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[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.

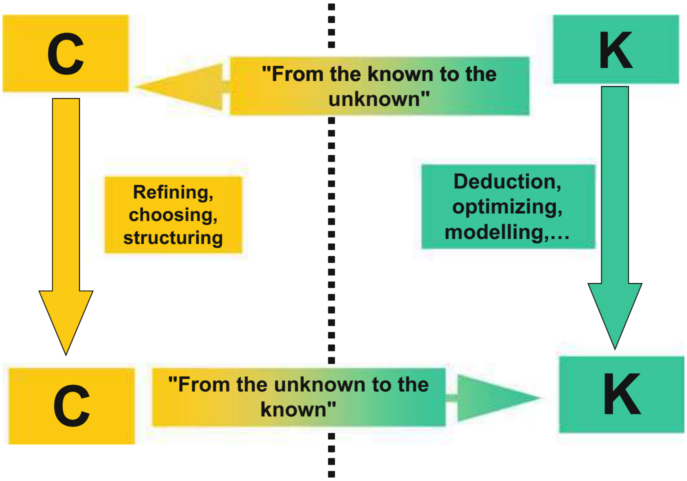

Fig. 4.2 The four operators in C-K theory: C ➔ K, K ➔ C, K ➔ K, C ➔ C

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.

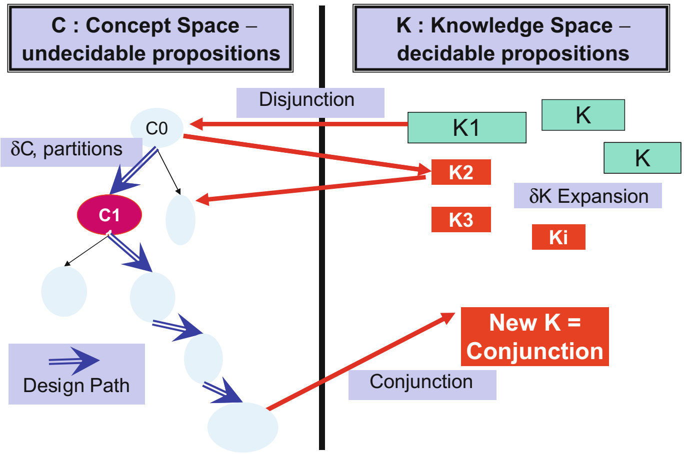

Fig. 4.3 The main ideas of C-K theory

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).

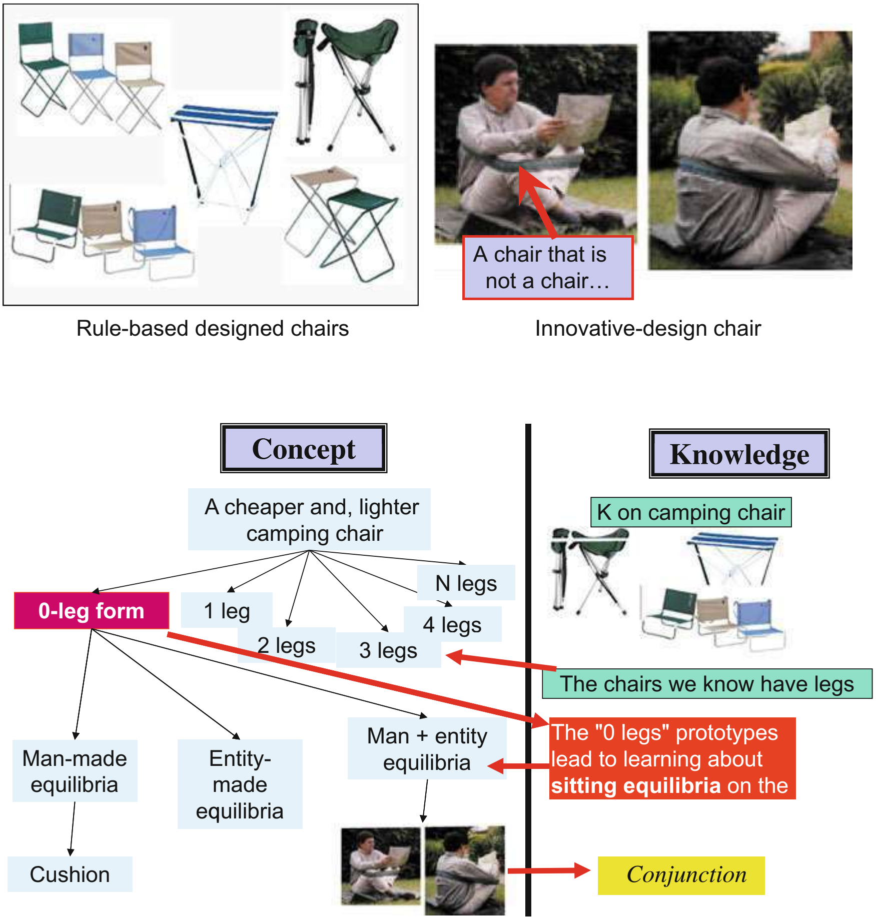

Fig. 4.4 Designing a cheaper and lighter camping chair. C-K theory allows a rigorous process of reasoning resulting in the so-called “Sangloyan” of Le Vieux Campeur or the Chairless of Vitra design; it also enables the systematic design of other “neighboring” objects sharing the definition of a legless, 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).

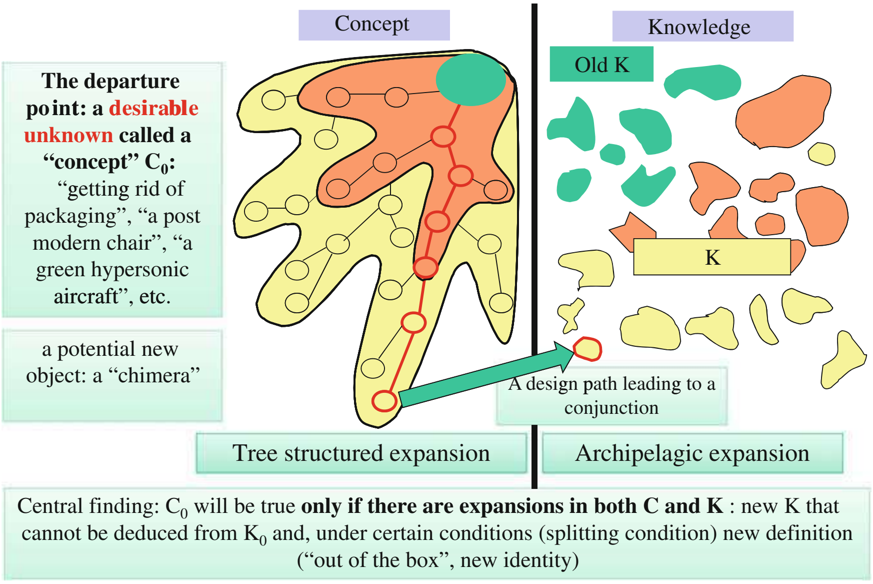

Fig. 4.5 A Synthesis of main notions of C-K theory

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).

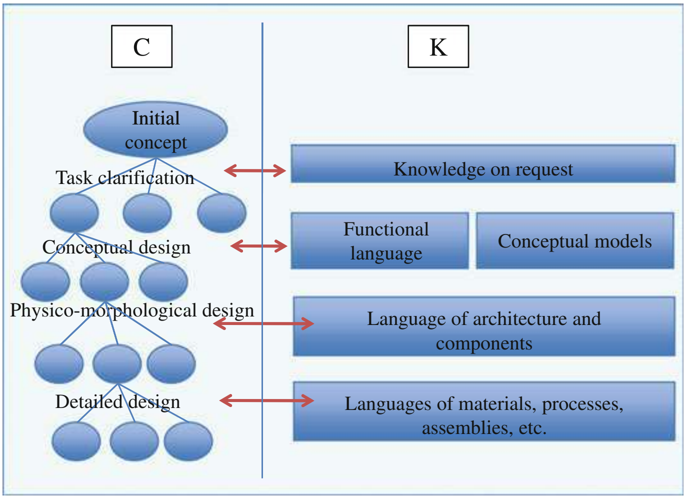

Fig. 4.6 Systematic design represented in C-K formalism

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.

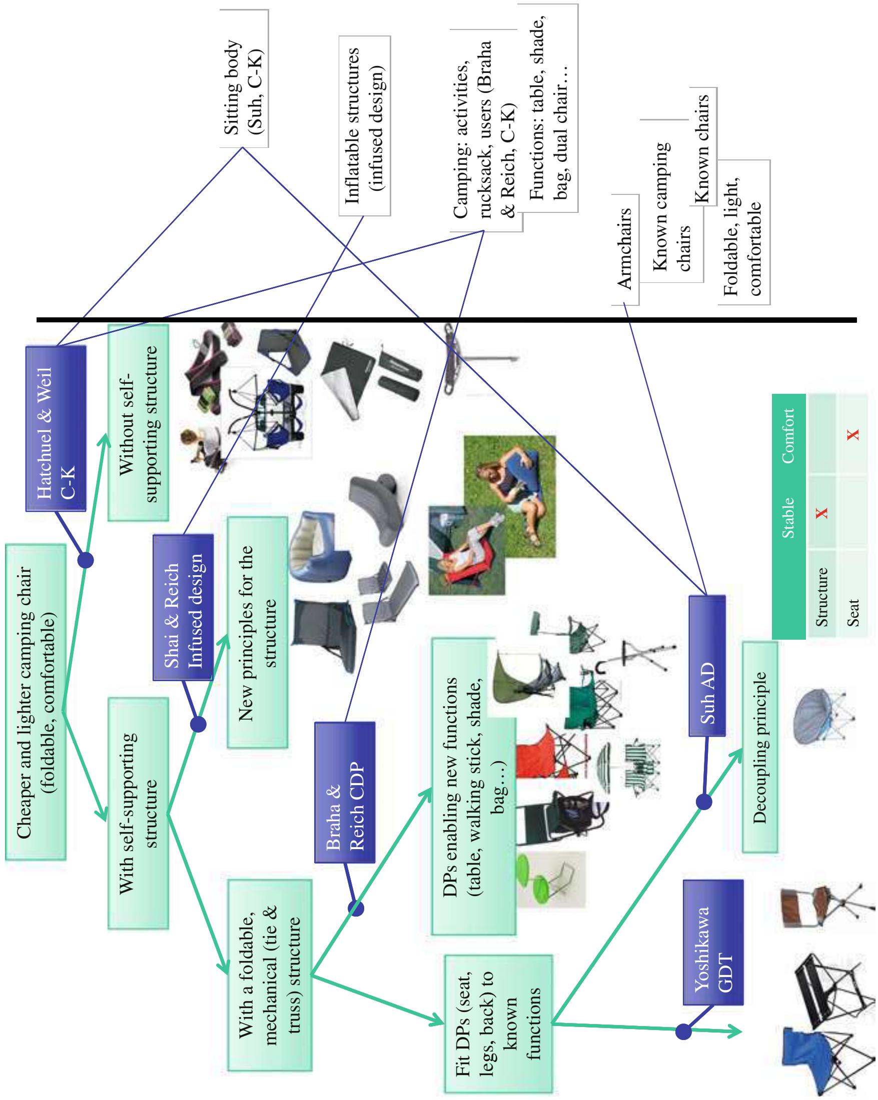

Fig. 4.7 A continuum of theories of design for a variety of generative forms

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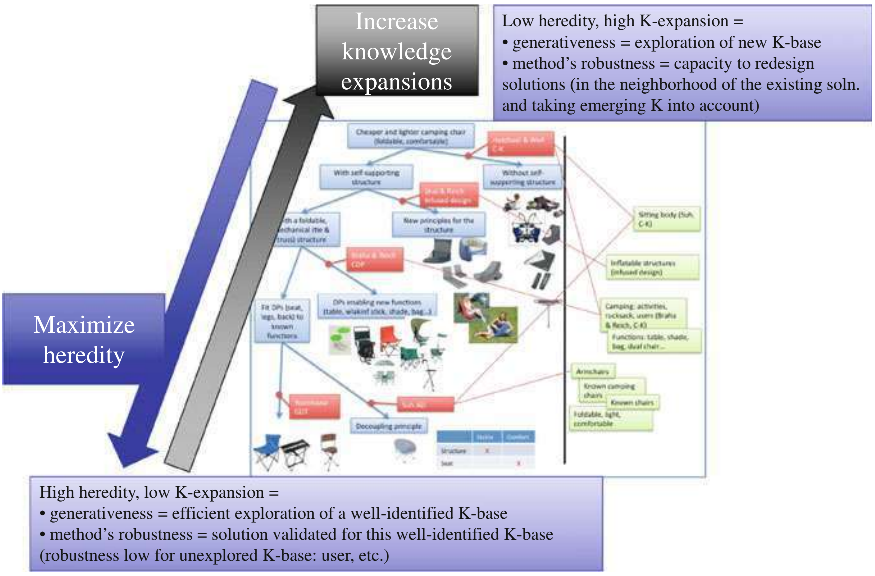

Fig. 4.8 Heredity and generative power

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 α is the root of the polynomial $X^2 + 1$ (in other words, α 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 α, 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, α 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 $a + b{\bullet}\alpha$ where a and b are in $\mathbb{R}$ and α satisfies $\alpha^2 + 1 = 0$ (we recognize the form of complex numbers where the common usage is to write α 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 α, 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

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[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, ($q(0)$, $q(1)$, … $q(\mathrm{k})$), there are always two conditions that refine q_k and are inconsistent ($q(0)$, $q(1)$,… $q(\mathrm{k})$, 0) and ($q(0)$, $q(1)$, … $q(\mathrm{k})$, 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:

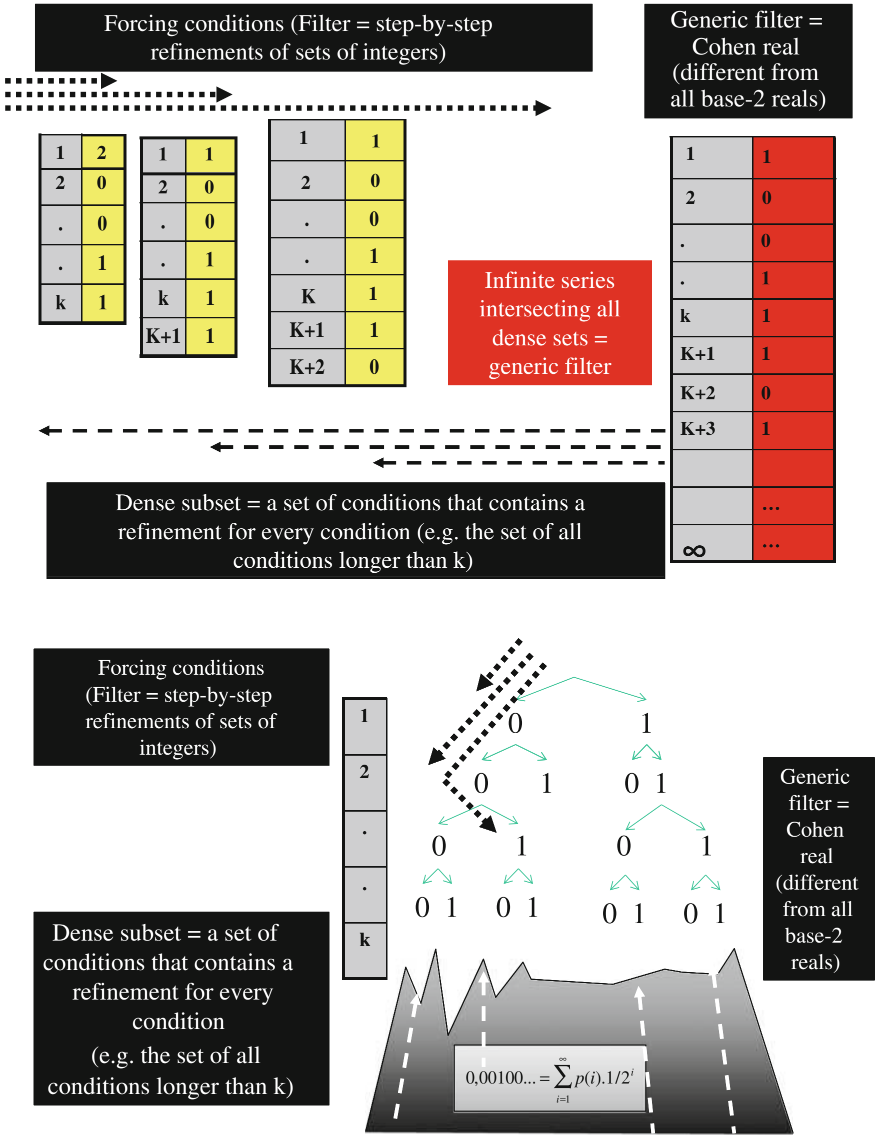

Fig. 4.9 Two representations of the creation of new real numbers by Paul Cohen

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

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[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).

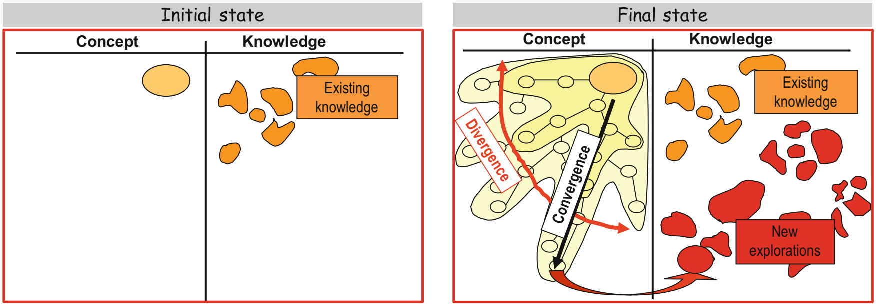

Fig. 4.10 Inputs and outputs for innovative design reasoning according to C-K theory

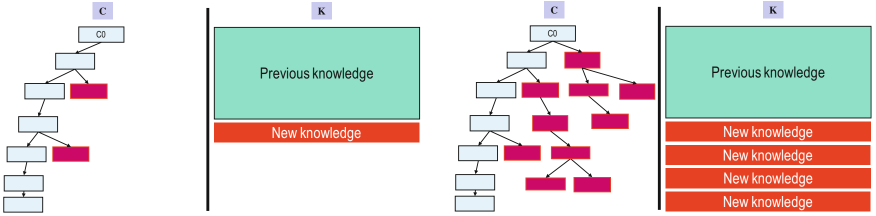

Fig. 4.11 Schematic representation in C-K of a “good” rule-based design exploration (***left***) and a “good” innovative design exploration (***right***)

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*

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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).

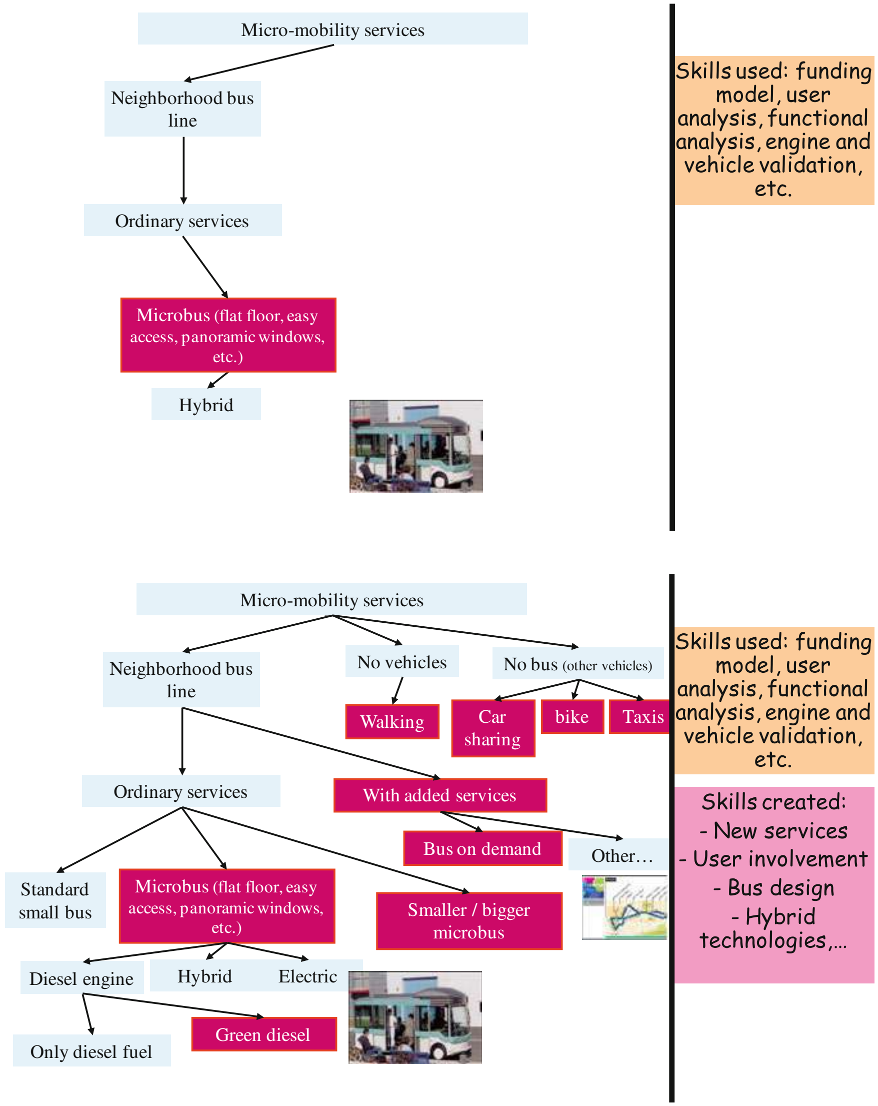

Fig. 4.12 Assessment of an innovative project: keeping only the main path/keeping all learned items. Within the standard CQT context (inherited from rule-based design projects) the project is perceived as a failure: it consumes many resources for a limited result (the first microbus was delivered late 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^* ...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 δC_0^* (new attributes added to C_0^*) and δK_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 δC_0^* and δK_0^* to bring what is extracted into the C_0-K_0. context. The

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[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

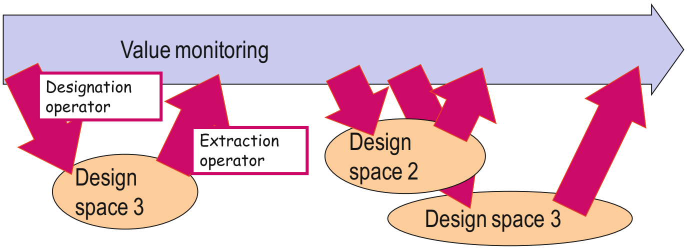

Fig. 4.13 Design Space and Value Management

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

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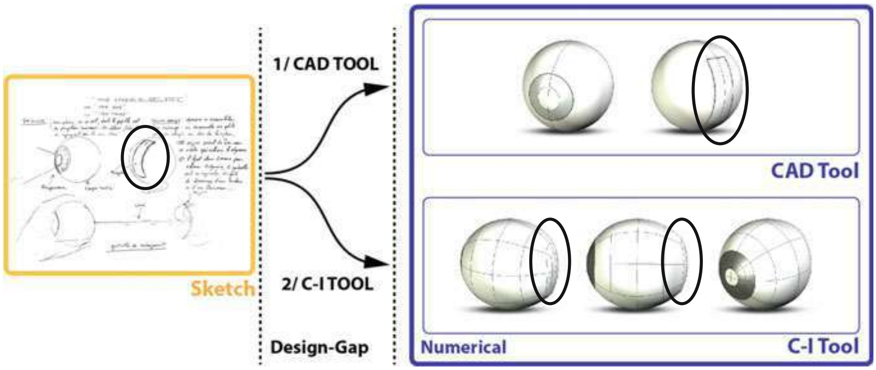

Fig. 4.14 New tools for the creative designer: a logical process of acquired originality (using this tool the designer can overcome the constraint (acquired robustness) while still being creative in how the constraint is satisfied—whence acquired originality

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):

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- 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.

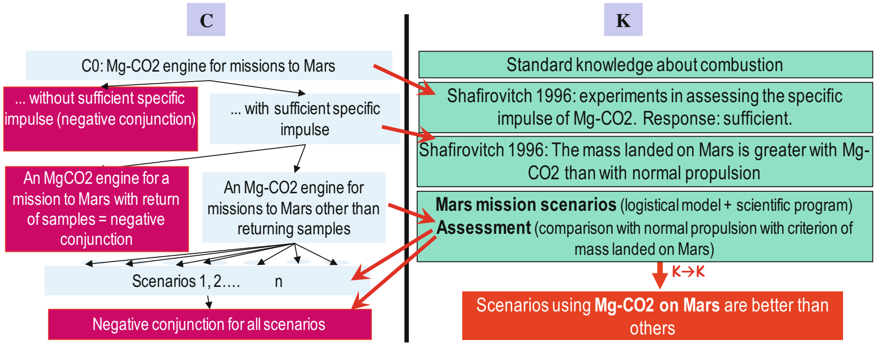

Fig. 4.15 "research" type and "development" type reasoning

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,

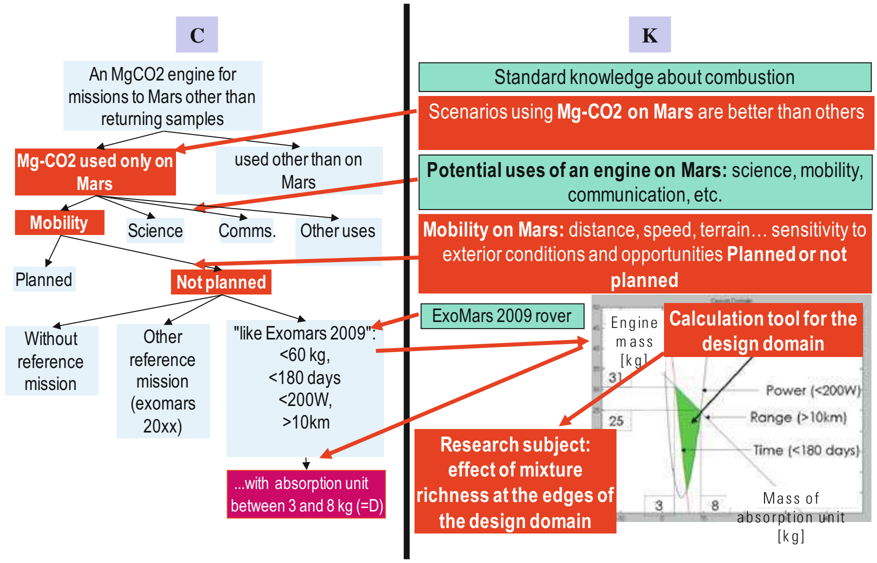

Fig. 4.16 Revision of the identity of the object. The hopper concept emerges. Reasoning continues until R&D starts

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.

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

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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

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[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,…”: 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.

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[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

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[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

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[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.

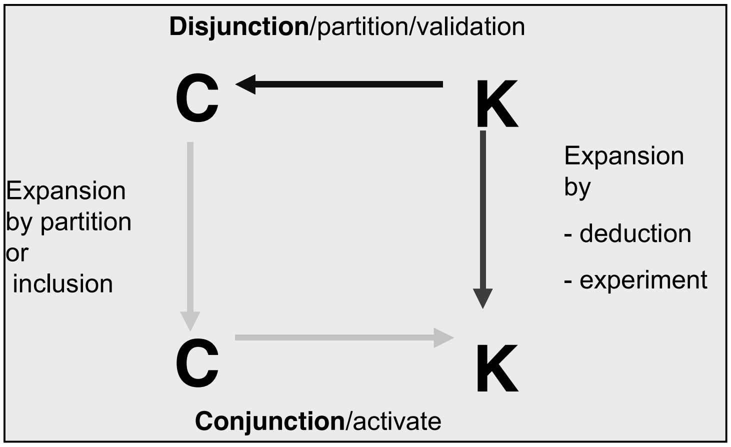

Figure 1. the design square

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".

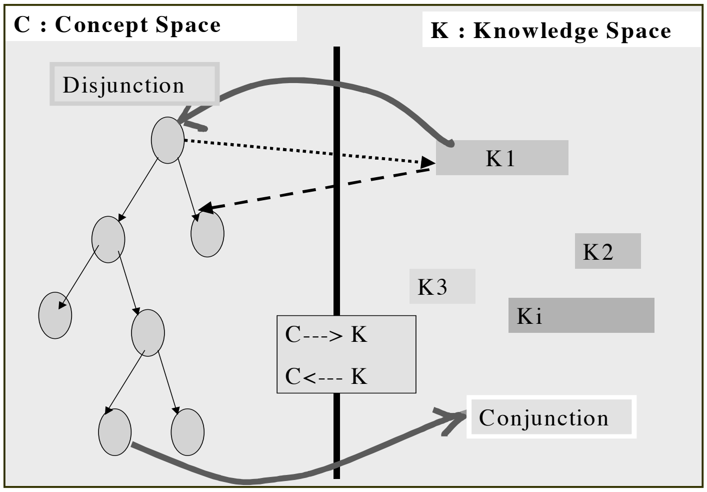

Figure 2. C-K dynamics

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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ORIGINAL PAPER

C-K design theory: an advanced formulation

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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]

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[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

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[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_is or the D_is;
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

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[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

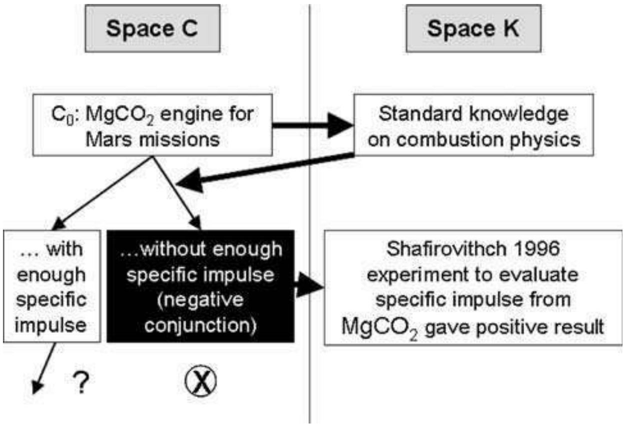

Fig. 1 Assesing a Concept of Mg-CO_2 engine

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[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 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.

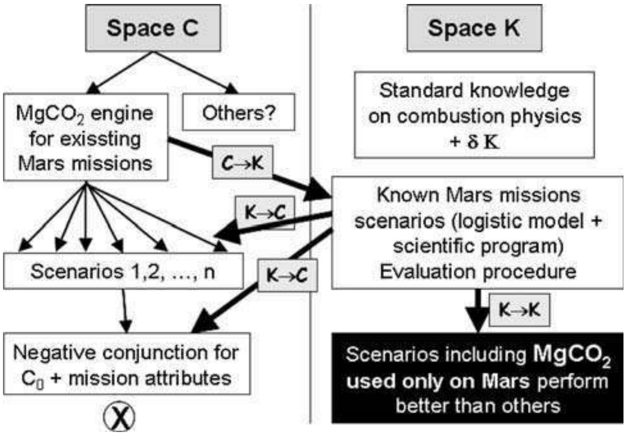

Fig. 2 Attributing known missions

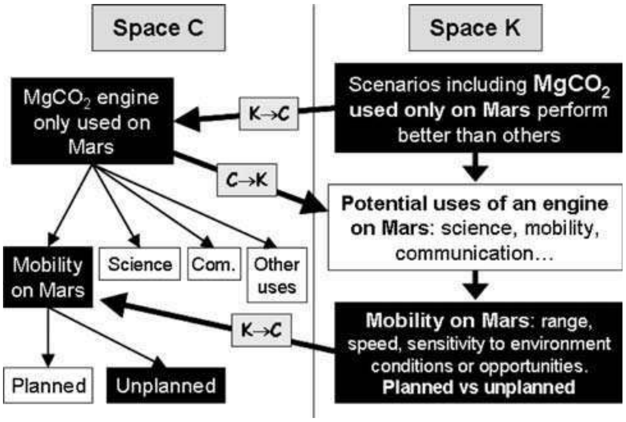

Fig. 3 Revisiting the identity of the engine

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

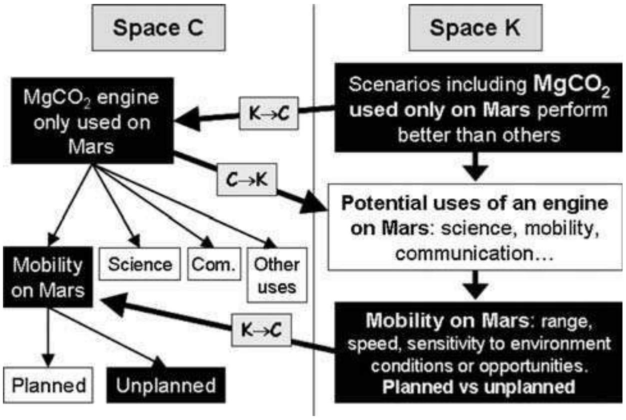

Fig. 4 Designing for prototyping

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

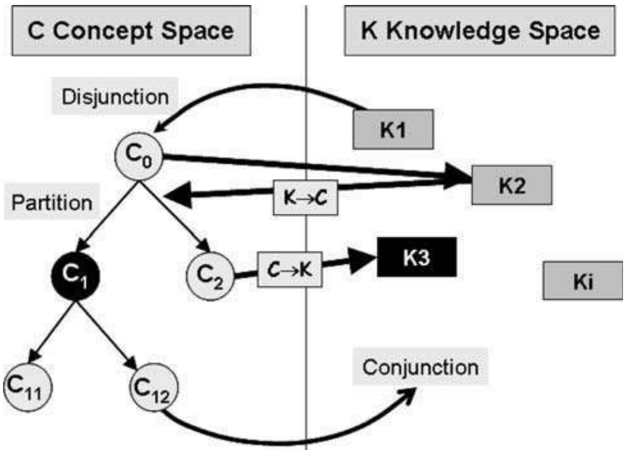

Fig. 5 Asymmetric structure of spaces C and K

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[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 Ds. 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.

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[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.

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[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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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:

Hatchuel, A (2013). Deconstructing meaning: Industrial design as Adornment and Wit. Mina Dennert. 10th European Academy of Design Conference: Crafting the Future, Apr 2013, Gothenburg, Sweden.

Le Masson, P., Hatchuel, A., & Weil, B. (2013). Teaching at Bauhaus: improving design capacities of creative people? From modular to generic creativity in design-driven innovation. In *10th European Academy of Design Conference: Crafting the Future* (pp. 23-p). University of Gothenburg.

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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

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[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

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[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

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[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

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[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.

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[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.

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[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.

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[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].

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[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*.

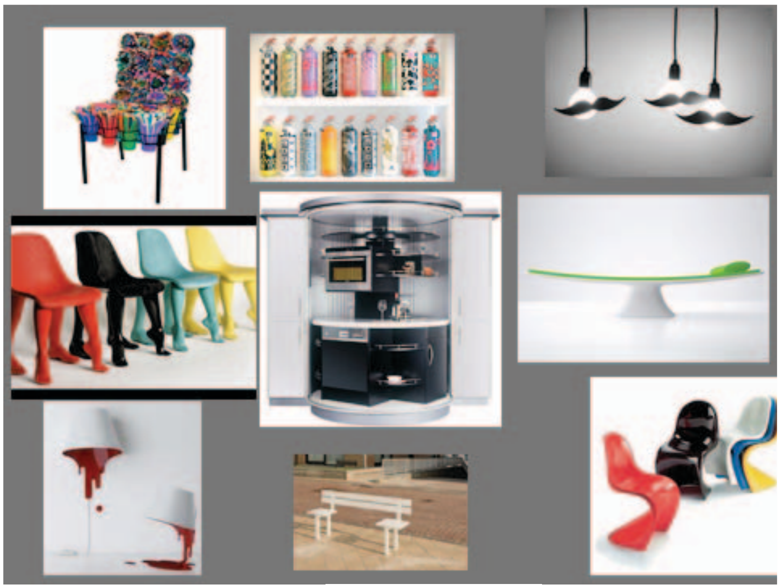

Fig 1

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.*

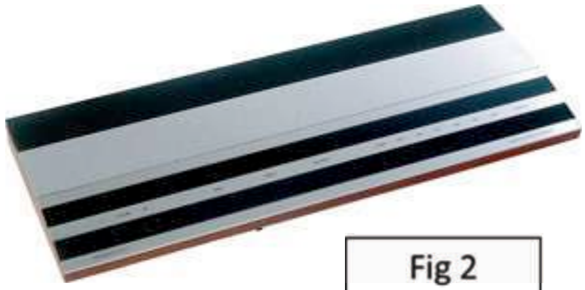

Fig 2

"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."*

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[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.

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[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

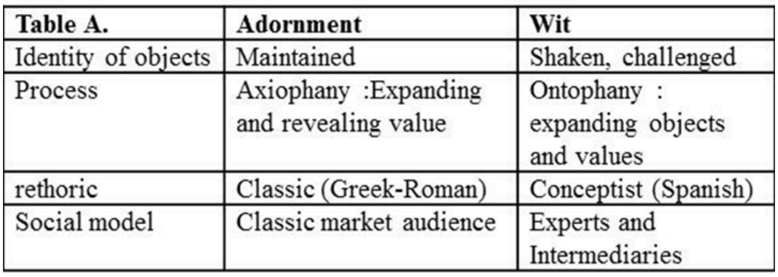

Table A.	Adornment	Wit
Identity of objects	Maintained	Shaken, challenged
Process	Axiophany :Expanding and revealing value	Ontophany : expanding objects and values
rethoric	Classic (Greek-Roman)	Conceptist (Spanish)
Social model	Classic market audience	Experts and Intermediaries

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:

- *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).

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[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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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

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[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.

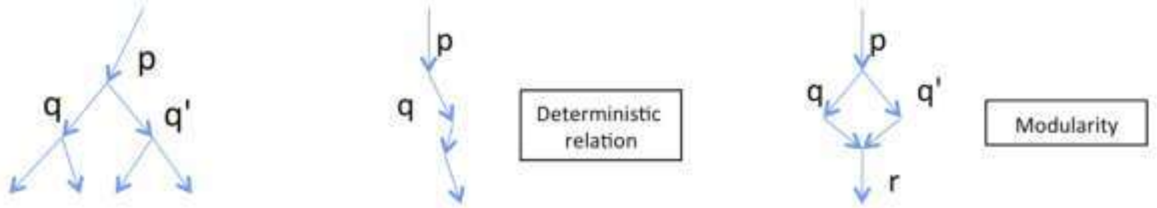

Figure 1: Splitting condition—left: constraints that follow the splitting condition; middle: a deterministic constraint p (non-splitting knowledge base); right: q and q′ are interchangeable modules (non-splitting knowledge base)

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 $\underline{p_0}$ 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 20th 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 19th 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 19th 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).

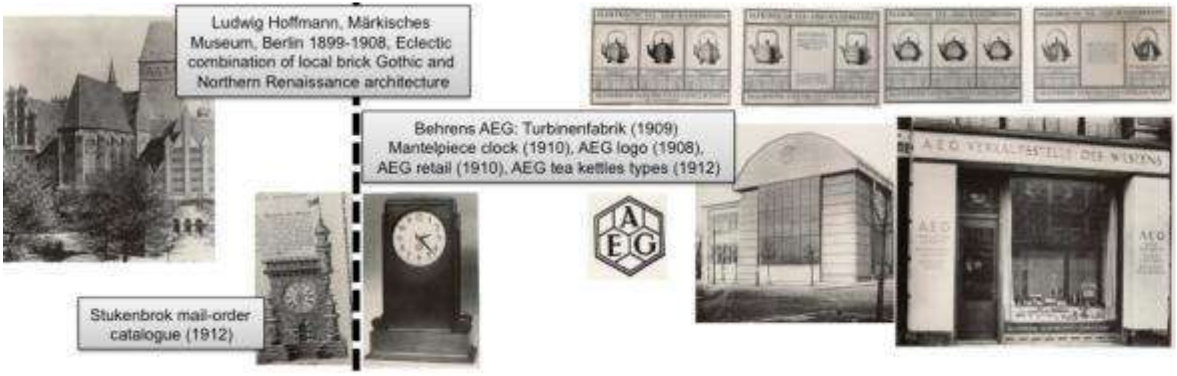

Figure 2: ‘Historical styles’ vs Behrens works at AEG in the 1900s–1910s. Left: one or multiple existing styles are used to design objects (a museum and a clock). Right: Behrens creates a new style coherent with many new objects (a clock, kettles, and new AEG domestic electric appliances) but also with a work environment (a factory), a retail environment (shop window) and a marketing environment (brands). (Source: adapted from (Schwartz 1996))

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[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.

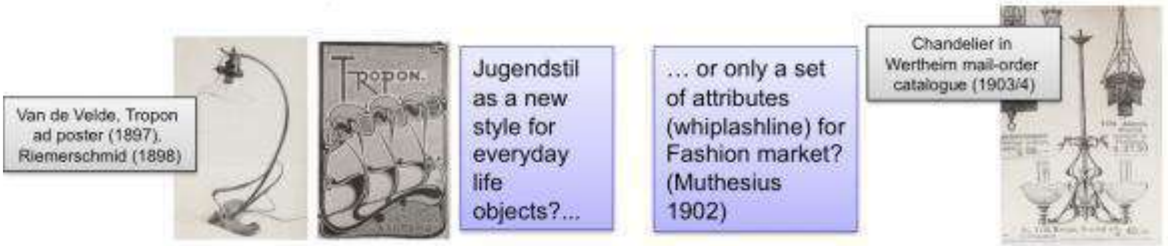


Figure 3: Jugendstil—inventing a new style (left) or just a fashionable ornament (right)? (Source: adapted from (Schwartz 1996))

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'.

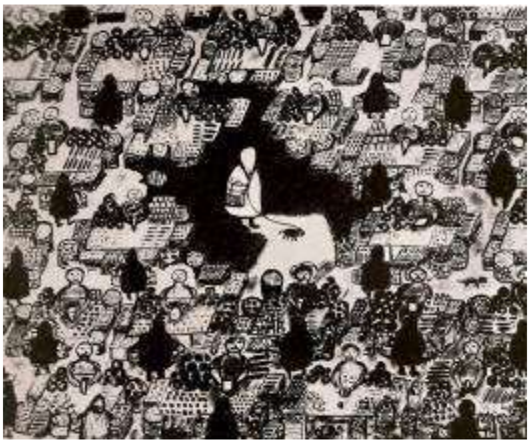


Figure 6: Characterization of environmental phenomena as textures (source: (Itten 1975))

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).

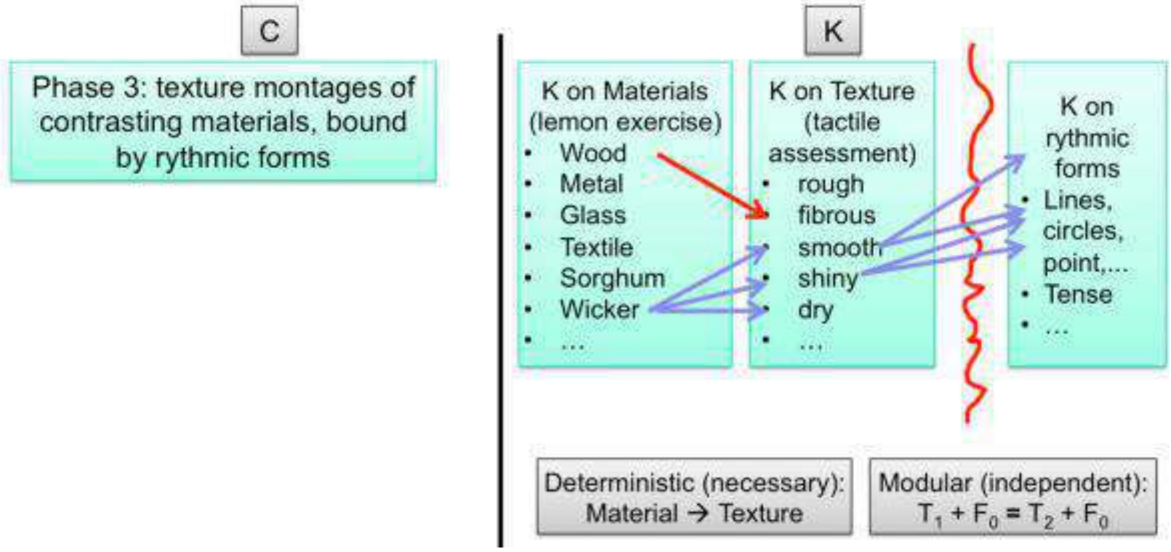


Figure 7: C-K analysis of one Itten exercise ('texture montage')—initial state

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.

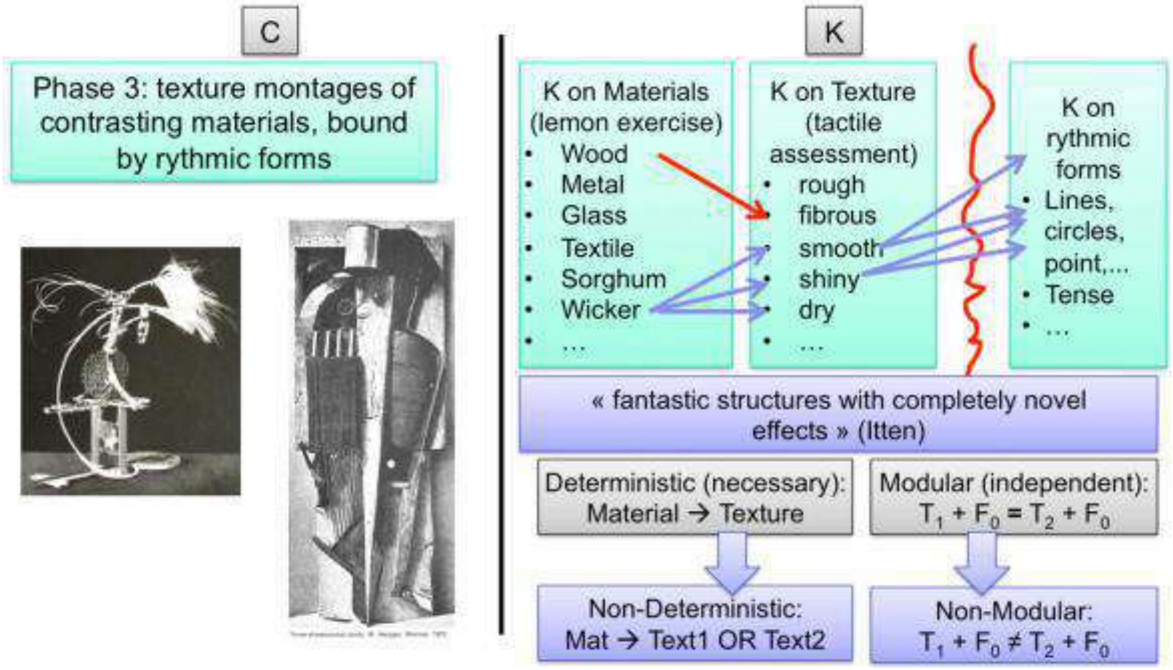


Figure 8: C-K analysis of one Itten exercise ('texture montage')—final state (sources for the pictures: (Max Bronstein 1921))

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).

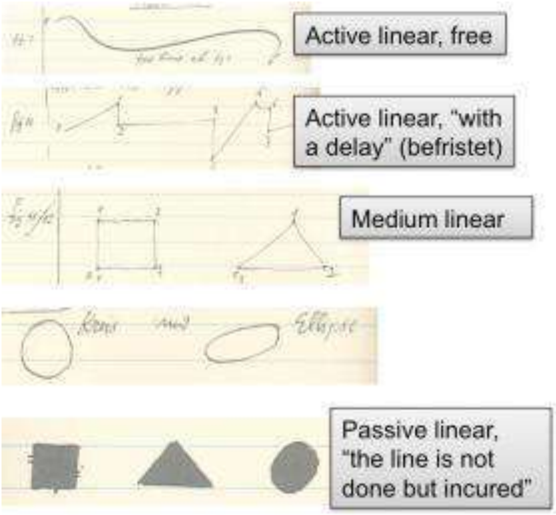


Figure 9: A new language for lines (source: (Klee 2005))

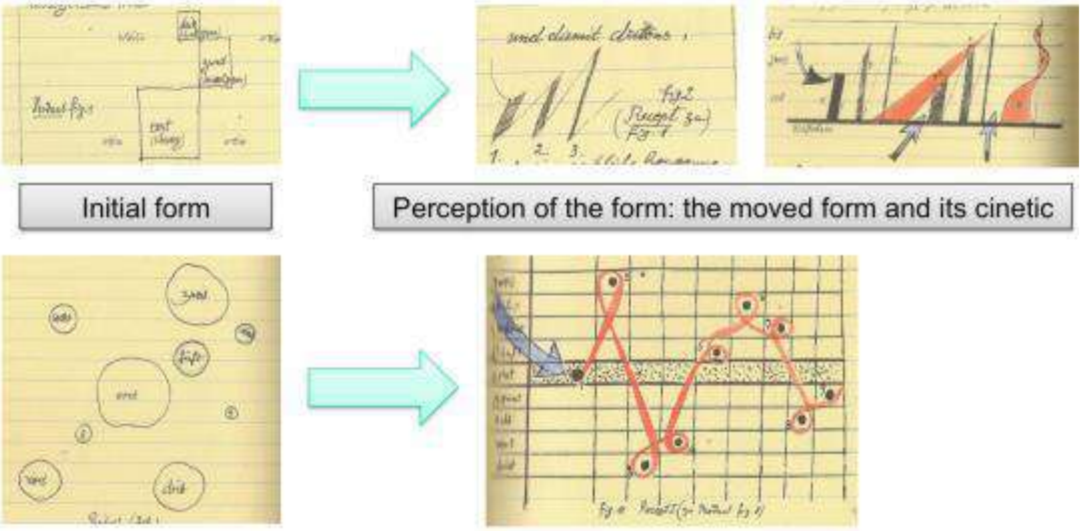
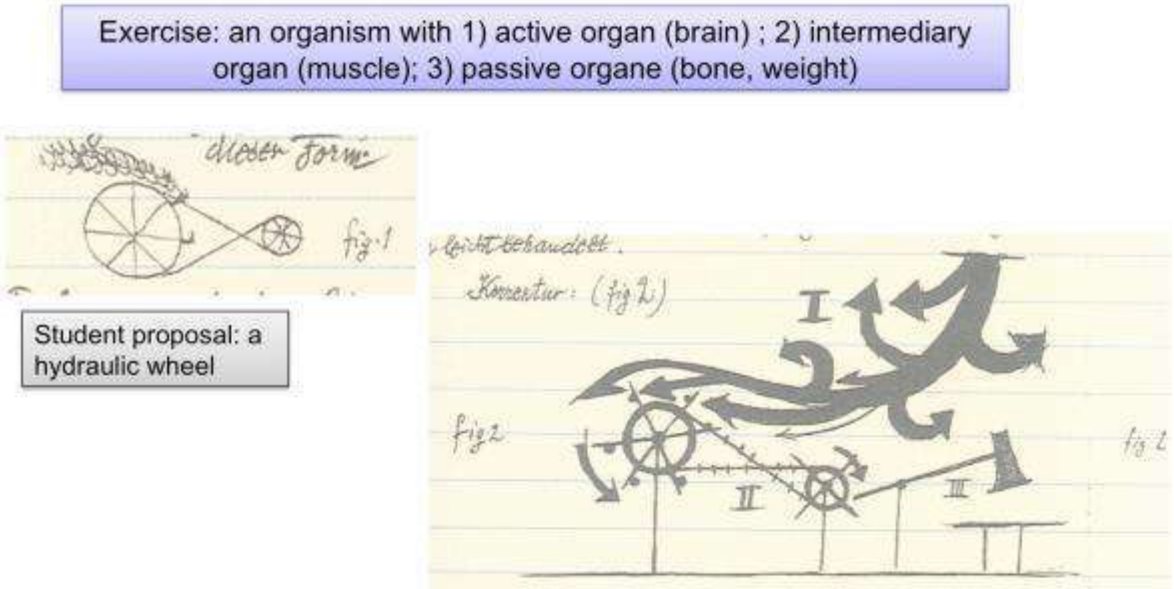


Figure 10: A language of perception: pasturage and predation; the kinetics of the moved form (source: adapted from (Klee 2005))

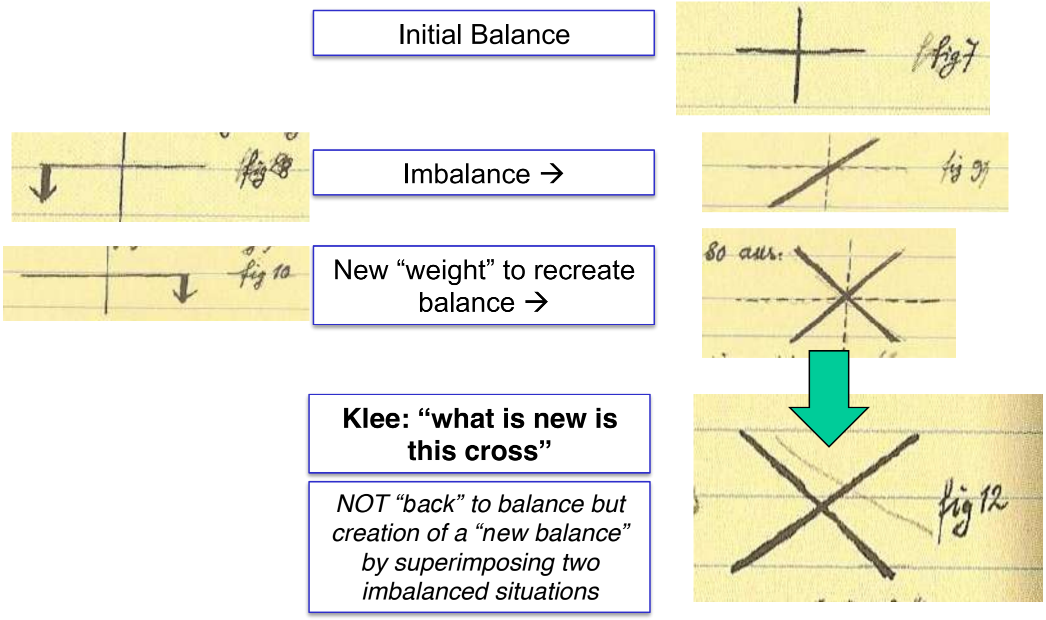
2- Each chapter of Klee's teaching not only investigates one dimension of the work (as did Itten for lines, surfaces, colour, textures, and so on) but discusses how one 'part' relates to the 'whole'. For instance, the 'line' is related to the 'perspective' of the whole piece, the 'weight' of each element 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).



Exercise: an organism with 1) active organ (brain) ; 2) intermediary organ (muscle); 3) passive organe (bone, weight)

Student proposal: a hydraulic wheel

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').



Initial Balance

Imbalance →

New "weight" to recreate balance →

Klee: "what is new is this cross"

NOT "back" to balance but creation of a "new balance" by superimposing two imbalanced situations

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’.

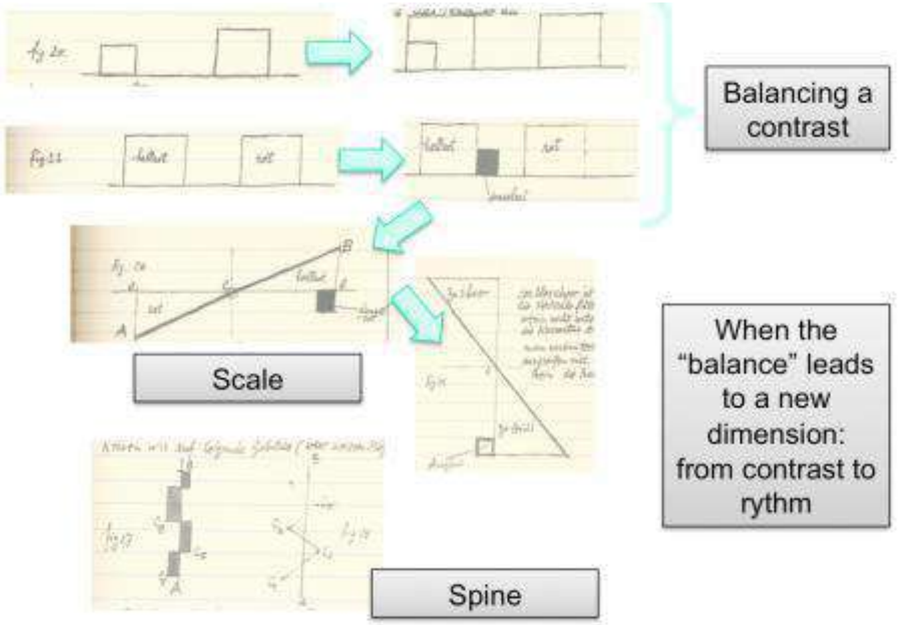


Figure 13: Shifting from one aspect to the following one—the case of balance and rhythms (source: adapted from (Klee 2005))

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.

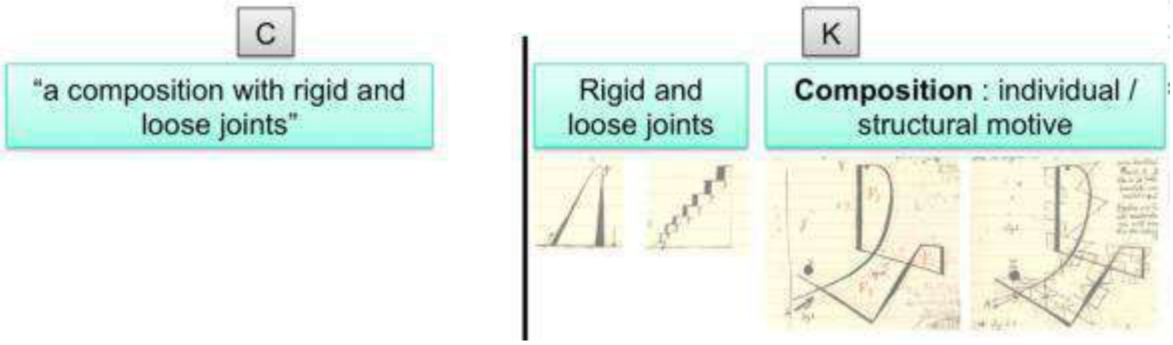


Figure 14: C-K analysis of one Klee exercise (‘joints and the individual‘)—initial state

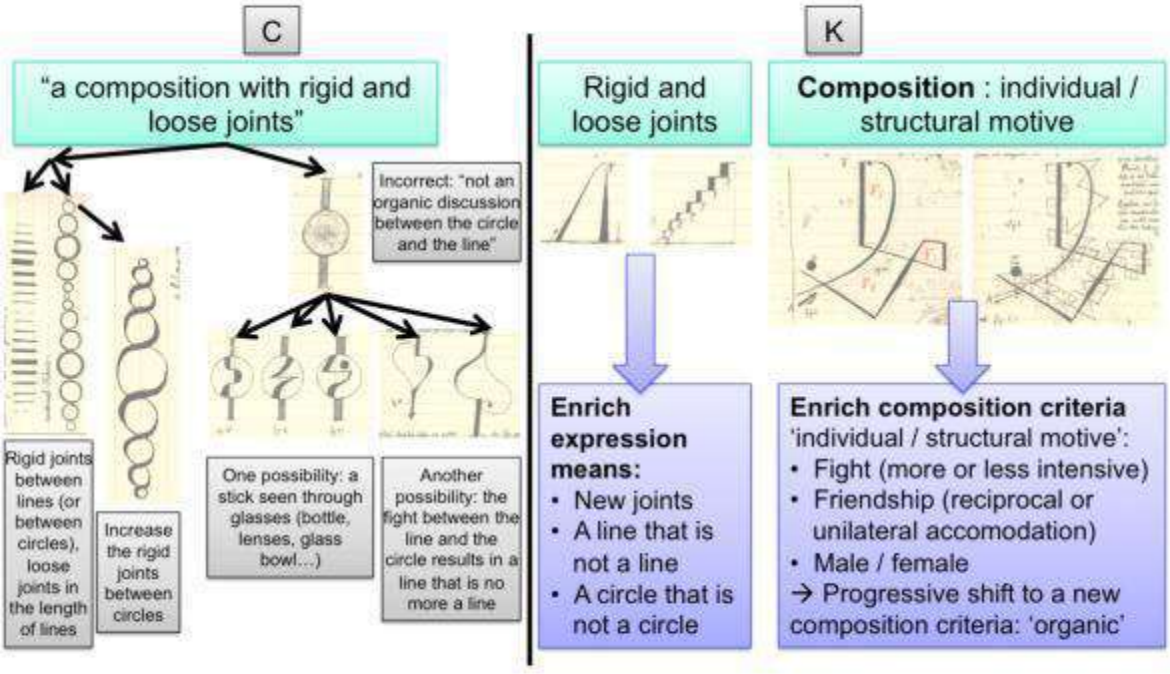


Figure 15: C-K analysis of one Klee exercise (‘joints and individual‘)—final state (pictures from (Klee 2005))

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 18th 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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Research interests:
Trans-disciplinary collaborative design
Front End of Discontinuous Innovation
Bio-inspired Industrial Design and Engineering
Organizational interface transitions in Open Innovation

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 $. 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: could Boeing have known that the way they organized the 787 development programme was not going to work?
Could Boeing have predicted the upcoming problems if they would have been knowledgeable of the existing design & innovation literature at the oment they took the decision late 90's? Did the literature of that time frame warn for the kind of problems Boeing started to face from mid 2007 till mid 2011, the time from the first roll out till the first delivery?
We will discuss possible answers to these questions in the light of the literature from the late 90's as a first step. As a second step we will look from the perspective of recent design & innovation literature.
Finally we will end up in the discussion about responsibilities of academics and industry at large, that is the theory-practice chasm.

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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

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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

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[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).

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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.

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[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.

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).

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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

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[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.

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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

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[5] The information presented here includes only publicly disclosed details and contains no confidential information about the program.

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

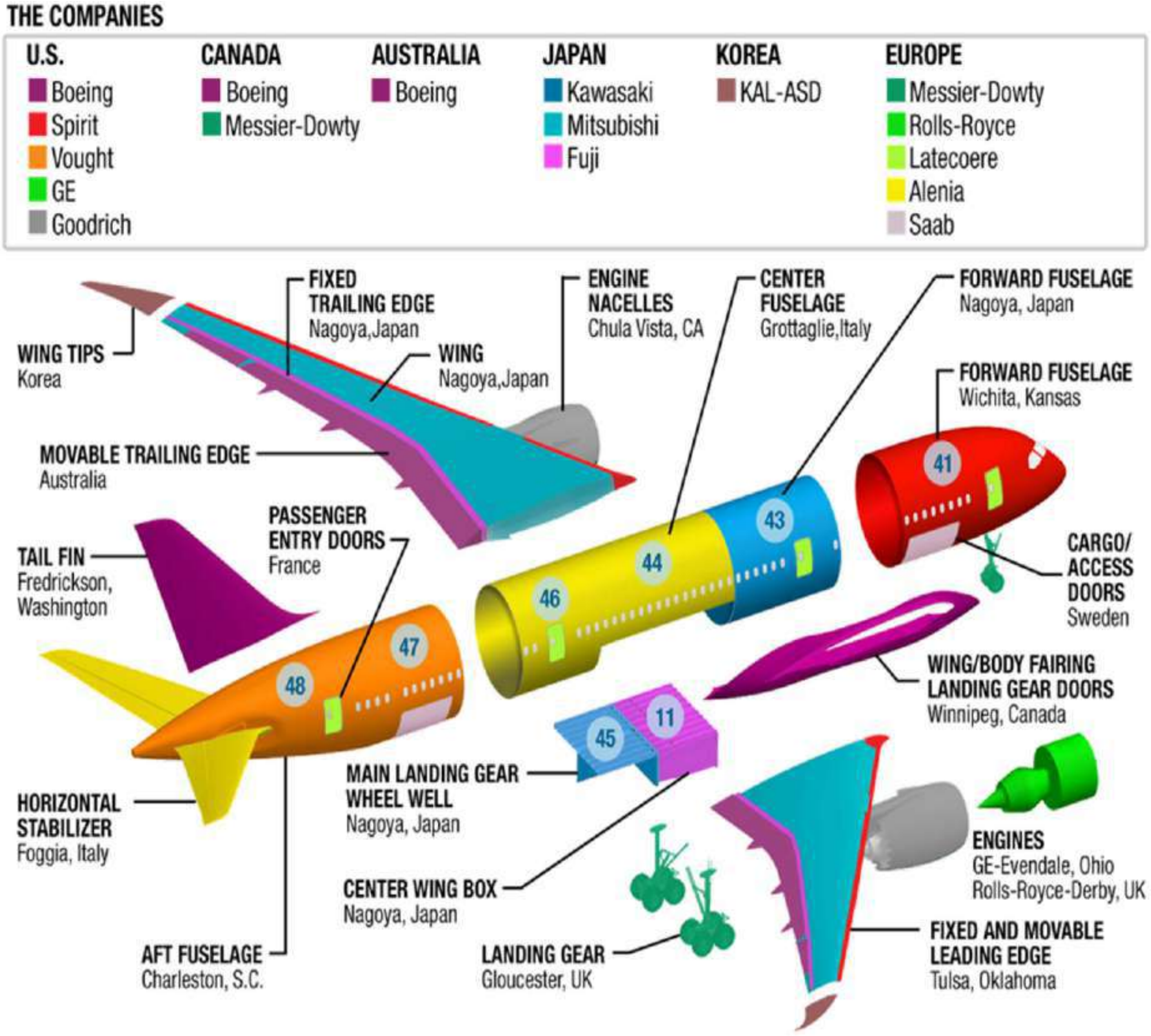

Figure 1. List of Boeing's global supplier partners for the 787 airplane
Source: Kotha and Nolan, 2005

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.

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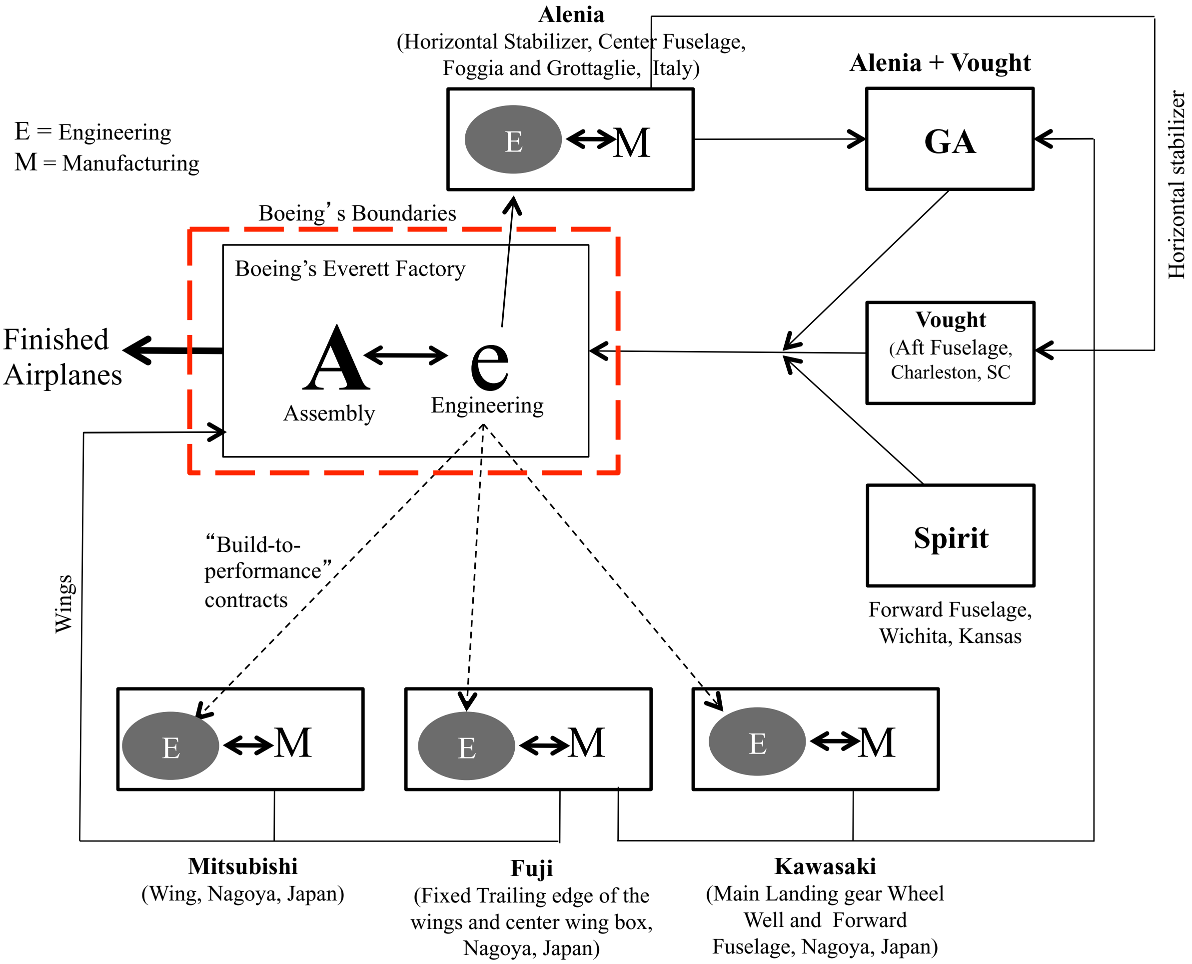

Figure 2. Simplified view of early architectural design for the 787 airplane, 2004
Source: Author's representation of Boeing's approach

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

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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. 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). 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.

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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

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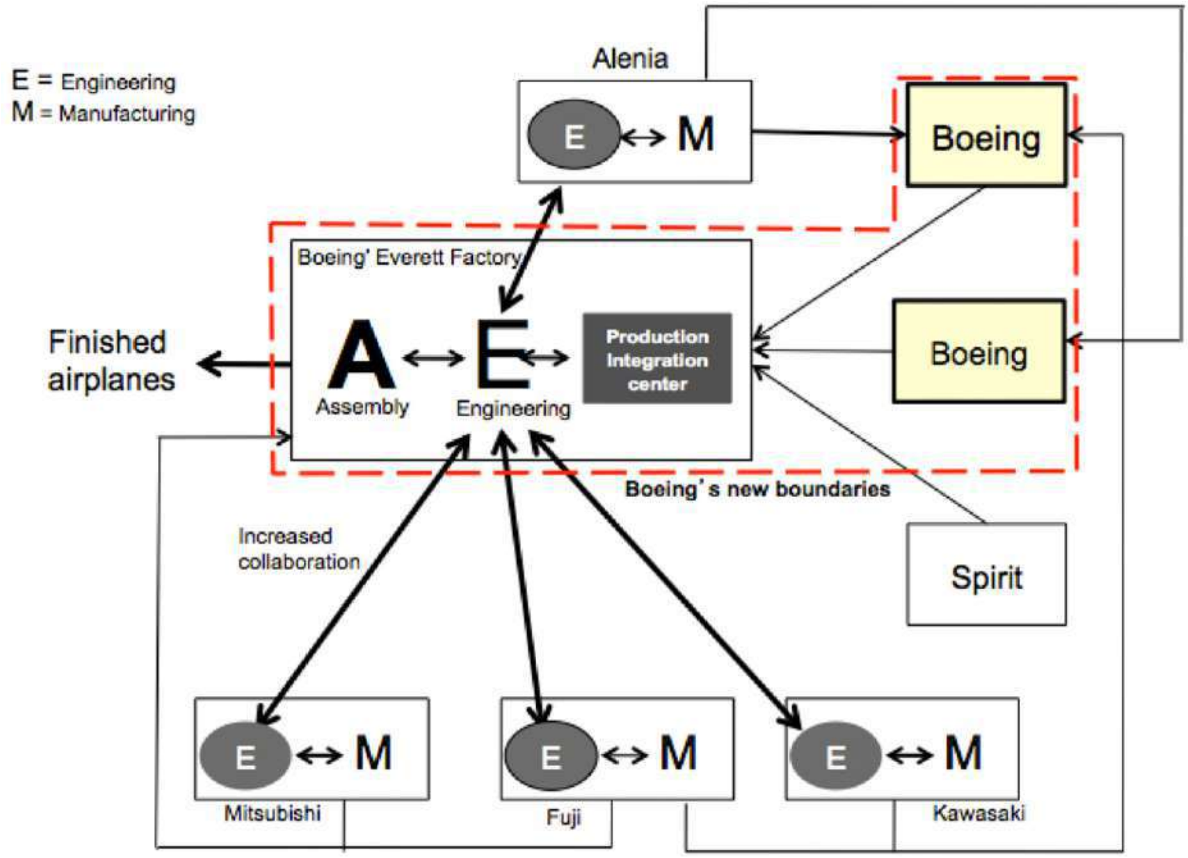

Figure 3. Simplified view of the changed architectural design for the 787 airplane, 2009
Source: Authors' representation of Boeing's approach

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

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[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.

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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.'

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[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).

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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 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 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.	Using data on incoming calls, managers were better informed about partner challenges and resources they need to resolve problems.
	Created a sense of urgency on the part of PIC managers to resolve problems at partner sites.	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.
		If certain calls were not resolved within a given time period, they were escalated to senior managers for resolution.
Coordinating air transportation 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 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.

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[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.

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]

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[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.

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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

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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

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[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.

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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

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[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.

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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. 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. 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. Creates a sense of urgency at Boeing to respond to requests for assistance. Also, top management can be informed or looped in, if needed. 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. Centralized tracking and monitoring enables effectively closing the loop on supply chain issues.

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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

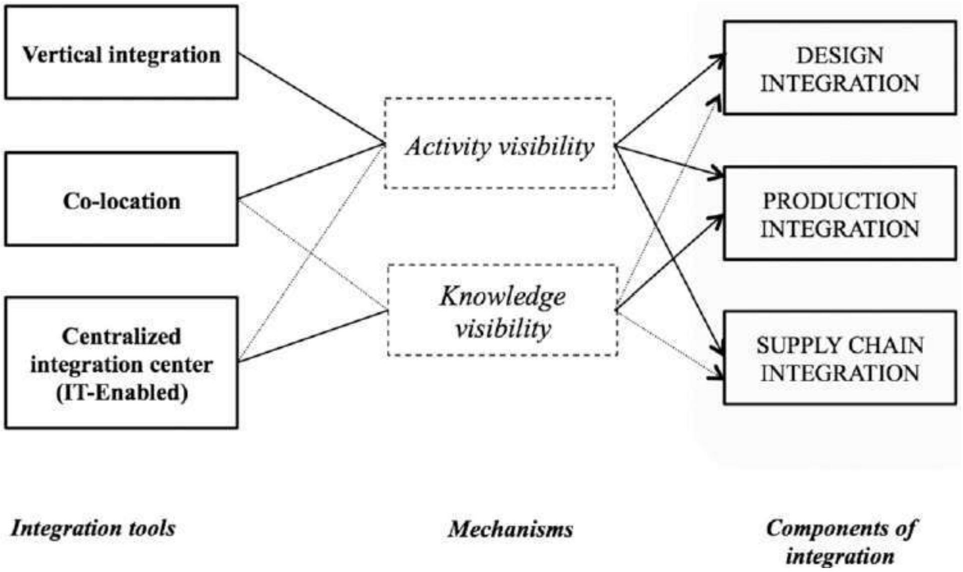

Figure 4. A proposed framework for achieving global integration

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.

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[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.

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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

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[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.

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.

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

Day 2 - 30 Jan 2019			
Timetable	**Type of Course**	**Title Course**	**Speakers**
9:00 - 10:00	**Basic course:** Contemporary Formal Models II	Knowledge structure in design (n-dim, category theory, matroïd, sp splitting condition)	Eswaran Subrahmanian & Blake Pollard
10:00 - 11:00	**Basic course:** Contemporary Formal Models III	Enhanced parameter analysis method	Ehud Kroll
11:00 - 11:30	**Break**		
11:30 - 12:30	**Basic course:** Contemporary Formal Models IV	An introduction to the PSI (Product - Social – Institutional) Framework	Yoram Reich
12:30 - 14:00	**Lunch**		
14:00 – 15:00	**Master class 1**		Professorial College
15:00 – 16:00	**Advanced topic / Paper discussion (2)**	Biomimetics with design theory (Vendôme classroom, visioconf)	Jacquelyn K.S. Nagel
16:00 - 16:30	**Break**		
16:30 - 17:30	**Advanced topic / Paper discussion (3)**	Axiomatic Design for Creativity, Sustainability, and Industry 4.0	Christopher Brown
17:30 – 19:30	**Cocktail**		

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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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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. 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)

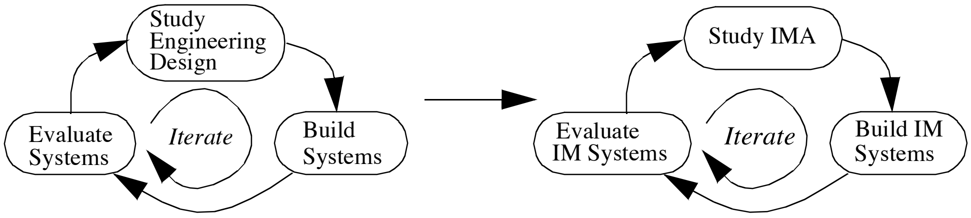
1. *Extended time*. Engineering activities extend over potentially long periods of time. The context of design must be maintained over that period and longer to allow for future reuse and for addressing life cycle issues.
2. *Multiple places*. Engineering activities take place in multiple locations which 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



(a) (b)

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 *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 *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.

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[2] This is an example of the use of social science approaches shown in Table 3.

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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:

$$\mathcal{N} = \left\{ \mathtt{Channel} \underset{\mathtt{target}}{\overset{\mathtt{source}}{\rightrightarrows}} \mathtt{Node} \right\} \tag{1}$$

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 $\leq n$:

$$\mathcal{H} = \left\{ 1 \xrightarrow{\mathtt{root}} \mathtt{Node} \circlearrowright \mathtt{parent} \mid \mathtt{parent}^n = \mathtt{const.root} \right\} \tag{2}$$

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

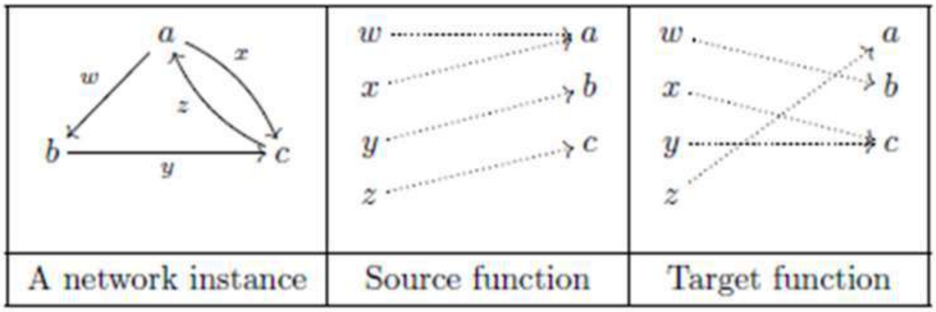


Fig. 1: Network as an $\mathcal{N}$-instance

$$\begin{tikzcd}
\mathtt{Channel} \arrow[r, "\mathtt{channel}"] \arrow[d, shift right, "\mathtt{source}"'] \arrow[d, shift left, "\mathtt{target}"] & \Gamma + \Delta \arrow[d, shift right, "\mathtt{id/id}"'] \arrow[d, shift left, "\mathtt{id/parent}"] \\
\mathtt{Node} \arrow[r, "\mathtt{layer}"'] & \mathtt{Layer} \arrow[loop right, "\mathtt{parent}"]
\end{tikzcd}$$

$$\Gamma = \Delta = \mathtt{Layer}$$

$$\mathtt{source.layer} = \mathtt{channel.id/id}$$

$$\mathtt{target.layer} = \mathtt{channel.id/parent}$$

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 $\mathtt{parent}^n = \mathtt{const.root}$ forces the nth 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

$$\begin{tikzcd}
\mathcal{N} \arrow[rr, "H"] & & \mathcal{H} \\
\mathtt{Channel} \arrow[rr, dotted] \arrow[d, shift right, "\mathtt{source}"'] \arrow[d, shift left, "\mathtt{target}"] & & \mathtt{Node} \arrow[d, shift right, "\mathtt{id}"'] \arrow[d, shift left, "\mathtt{parent}"] \\
\mathtt{Node} \arrow[rr, dotted] & & \mathtt{Node}
\end{tikzcd}$$

(a) A single functor

$$\begin{tikzcd}
\mathcal{N} \arrow[rr, "H"] \arrow[dr, bend right, "C"'] \arrow[dr, "L'"] & & \mathcal{H} \arrow[dl, "L"] \\
& \mathcal{L} &
\end{tikzcd}$$

(b) A diagram of functors

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].

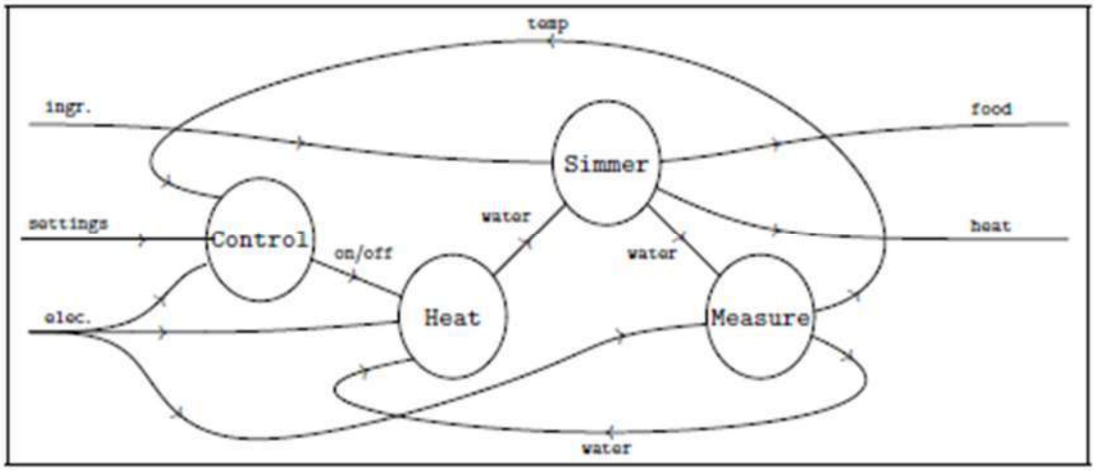


Fig. 4: Process decomposition as a string diagram

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).

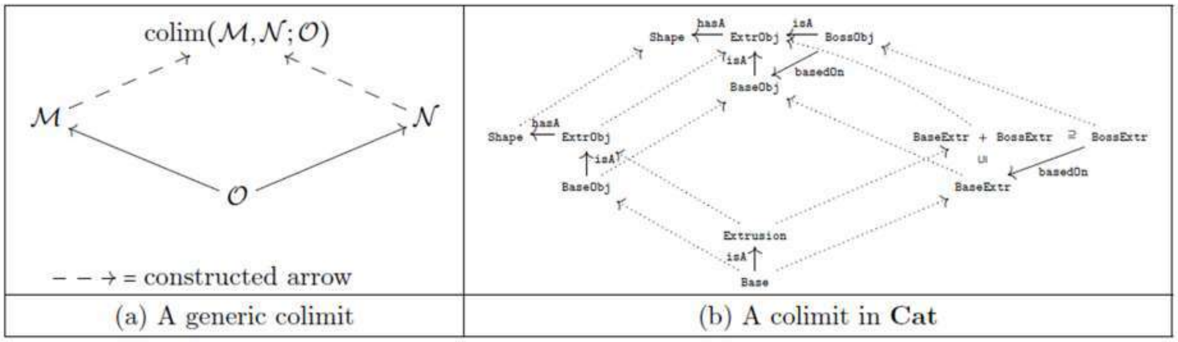
The satisfaction relation for the semantic interpretation is determined by the preservation of categorical structure. A good example is the coproduct "+", used in our model for the layered architecture $\mathcal{L}$ (figure 3). Not all functors $\mathcal{L} \to \mathbf{Sets}$ are semantically valid, 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 $\mathcal{H} \rightarrow \mathrm{colim}(\mathcal{M},\mathcal{N};\mathcal{O})$ 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 $\mathcal{N} \rightarrow \mathbf{Sets}$ 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 proceeded to define a functor $\mathcal{N} \rightarrow \mathcal{H}$. The direction has reversed!

The categorical formulation explains this fact: given a functor $\mathcal{N} \rightarrow \mathcal{H}$ and an instance $\mathcal{H} \rightarrow \mathbf{Sets}$, we can compose these at $\mathcal{H}$ to obtain an instance $\mathcal{N} \rightarrow \mathbf{Sets}$. 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 $\mathcal{N} \rightarrow \mathcal{N}'$. A categorical construction principle for the colimit then guarantees that we can build a new map $\mathrm{colim}(\mathcal{M},\mathcal{N};\mathcal{O}) \rightarrow \mathrm{colim}(\mathcal{M},\mathcal{N}';\mathcal{O})$. 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 represenitic 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.

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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:

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ORIGINAL PAPER

Steepest-first exploration with learning-based path evaluation: uncovering the design strategy of parameter analysis with C–K theory

Ehud Kroll · Pascal Le Masson · Benoit Weil

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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

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[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.

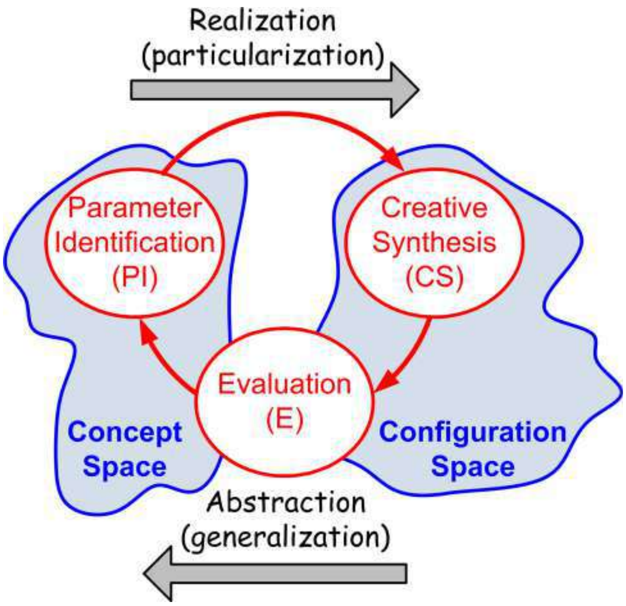


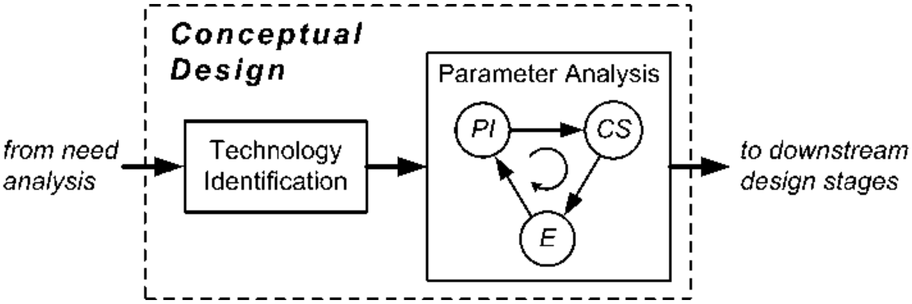
Fig. 1 The prescriptive model of PA consists of repeatedly applying parameter identification (PI), creative synthesis (CS) and evaluation (E). The descriptive model of moving back and forth between concept space and configuration space is also shown

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:

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[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

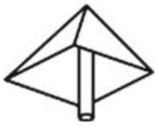
Parameter Analysis Terminology	***Reasoning Process***	***Outcome***
Design task statement	None (the "brief" is provided by the customer)	Design the decelerators for the given sensors and their means of packing and deployment in the air.
Need Analysis	Not described here. Can be done in several ways, such as QFD. It turns the "brief" into design requirements (specs.)	Design requirements: 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: 1. Flexible parachute 2. Rigid parachute 3. Balloon filled with light gas 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 ~150 mm. If the decelerator is a flat disk perpendicular to the flow, the C_D reduces to ~1.2, and if it is a sphere, then $C_D \cong 0.5$, with the corresponding diameters being

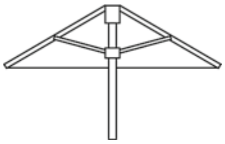
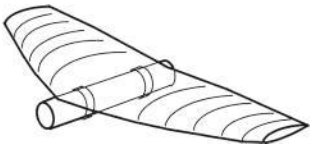
PI_3	How can the last configuration be improved? Combine the idea of flexible parachute that can be folded for packing with a rigid parachute that doesn't have cords and doesn't require a strong "pull" to open.	Parameter: "Use a frame + flexible sheet construction that can fold like an umbrella; use 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 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.

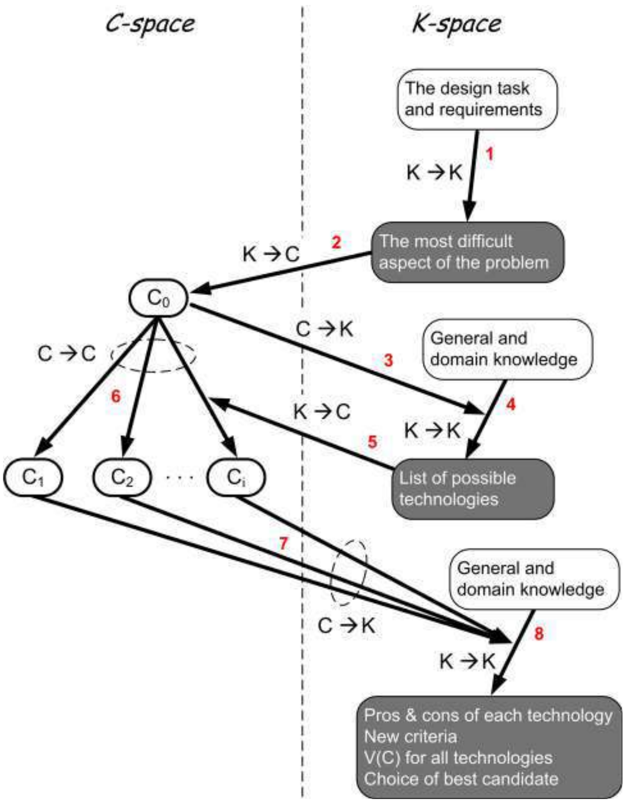


Fig. 4 Modeling the technology identification (TI) stage in C–K theory terms. The root concept C_0 is established, possible technologies identified and evaluated, yielding a value V(C) for all concepts. Finally, the best candidate is selected for further development

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.

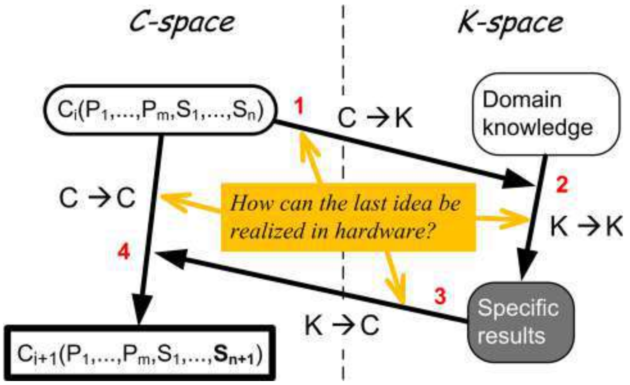


Fig. 5 Modeling the creative synthesis (CS) step in C–K theory terms. The latest ideational attribute P_m of concept C_i (which corresponds to a PA parameter) is implemented as structural attribute S_{n+1} of concept C_{i+1}

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.

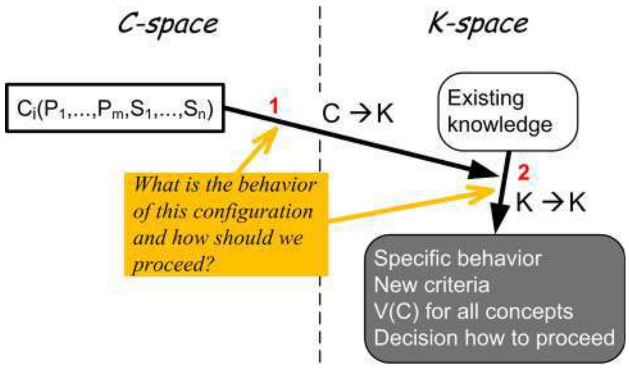


Fig. 6 Modeling the evaluation (E) step in C–K theory terms. Concept C_i corresponds to a PA configuration and existing knowledge is used to derive its behavior, deduce new evaluation criteria, calculate values V(C) for all pending concepts including C_i and make the decision as to how to proceed. The 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.

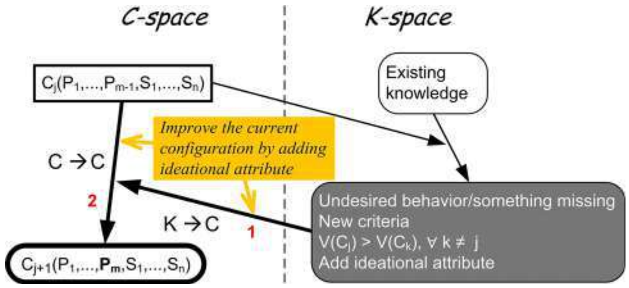


Fig. 7 Modeling the common occurrence of the parameter identification (PI) step in C–K theory terms following case (2) of evaluation (following the current path). Concept C_j has been evaluated (*thin arrows*) and weaknesses found. New criteria may be generated accordingly, but the value of C_j is still the highest, so ideational attribute P_m is added to form a new concept C_{j+1}

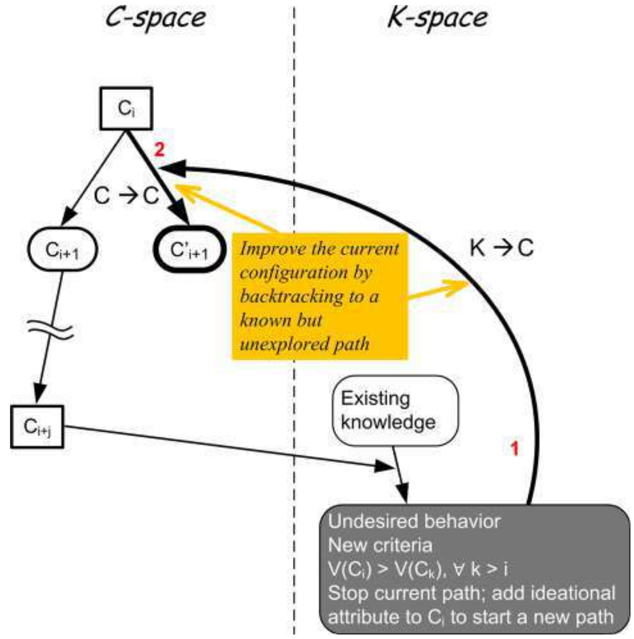


Fig. 8 Modeling the parameter identification (PI) step in C–K theory terms following case (3) of evaluation (backtracking to a known but unexplored path), with backtracking to a previous concept whose value suddenly becomes the highest. An ideational attribute P'_m is added to C_i and creates a path 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

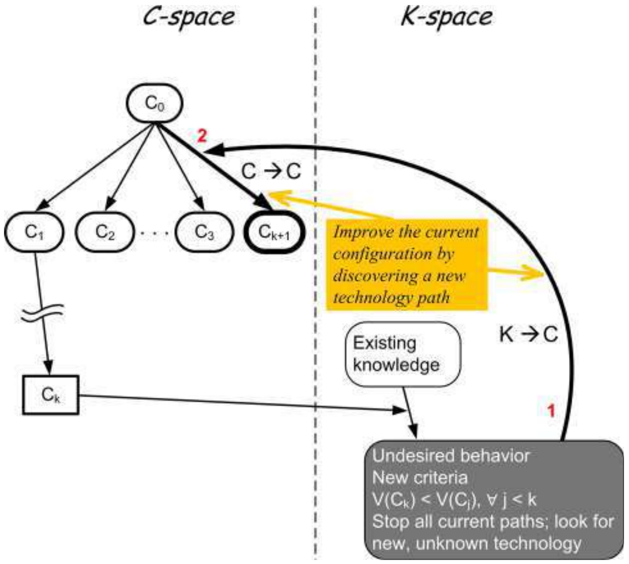


Fig. 9 Modeling the parameter identification (PI) step in C–K theory terms following case (4) of evaluation (backtracking to an unknown path), with backtracking to the root concept in order to *discover* a new technology. This implies discarding all the previous attributes and starting over

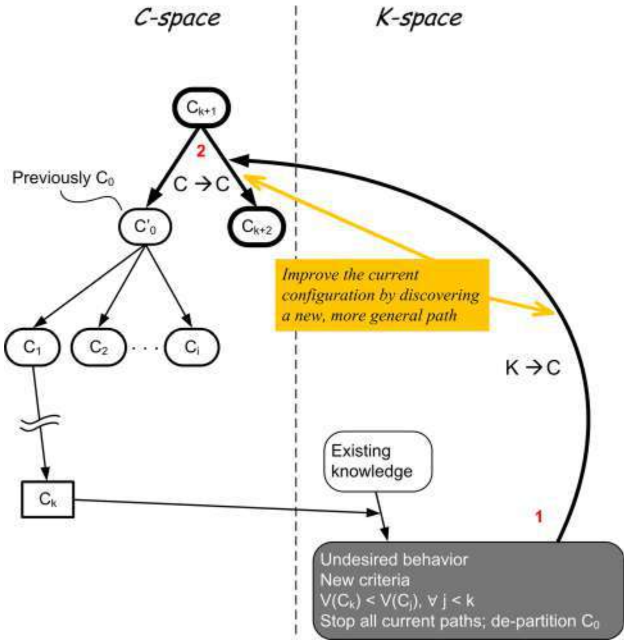


Fig. 10 Modeling the parameter identification (PI) step in C–K theory terms following case (4) of evaluation (backtracking to an unknown path), with backtracking to *higher* than the root concept in order to revise its identity. C_{k+1} becomes the new, more general root concept; C'_0 is a revised version of the previous root concept C_0; C_{k+2} is the beginning of a new, perhaps surprising path

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 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

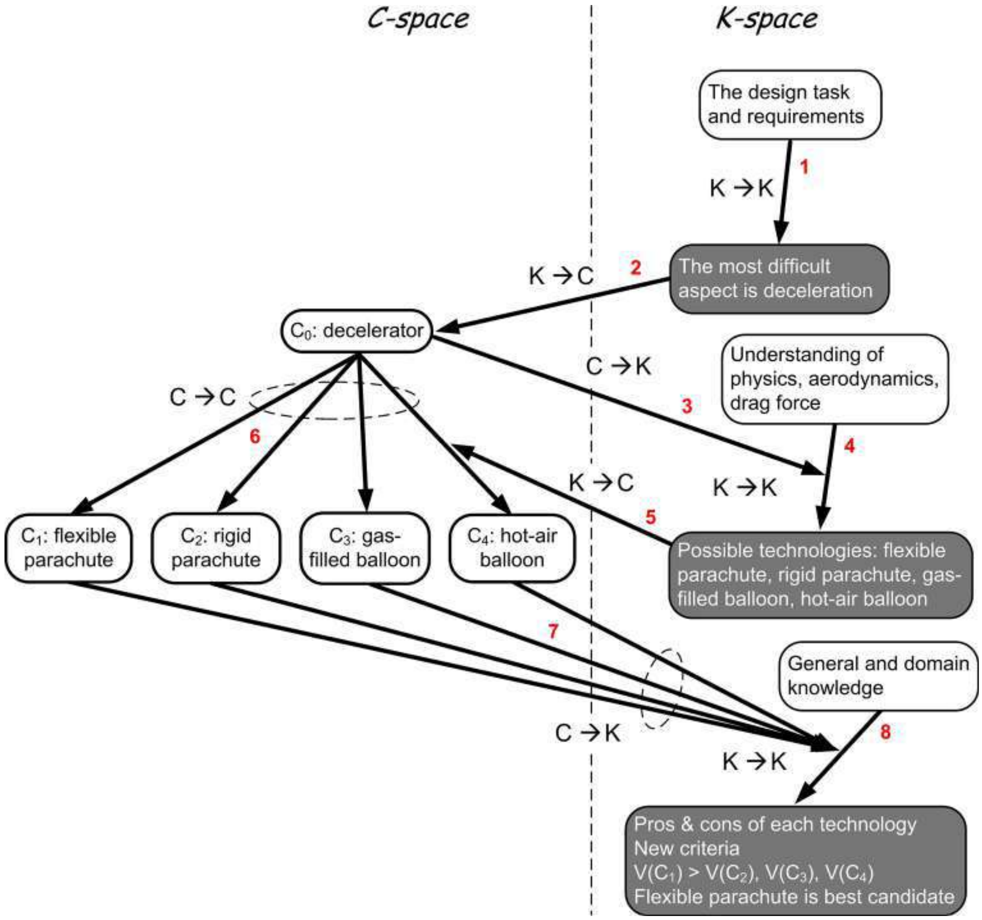


Fig. 11 C–K modeling of the technology identification (TI) stage of the decelerator design example. Producing drag force, simplicity and compact packing are used as evaluation criteria to assign the highest value to C_1, thus initiating a design path based on flexible parachute

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 $C_0 = \textit{decelerator}$ to $C_0' = \textit{vertical drag decelerator}$ 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

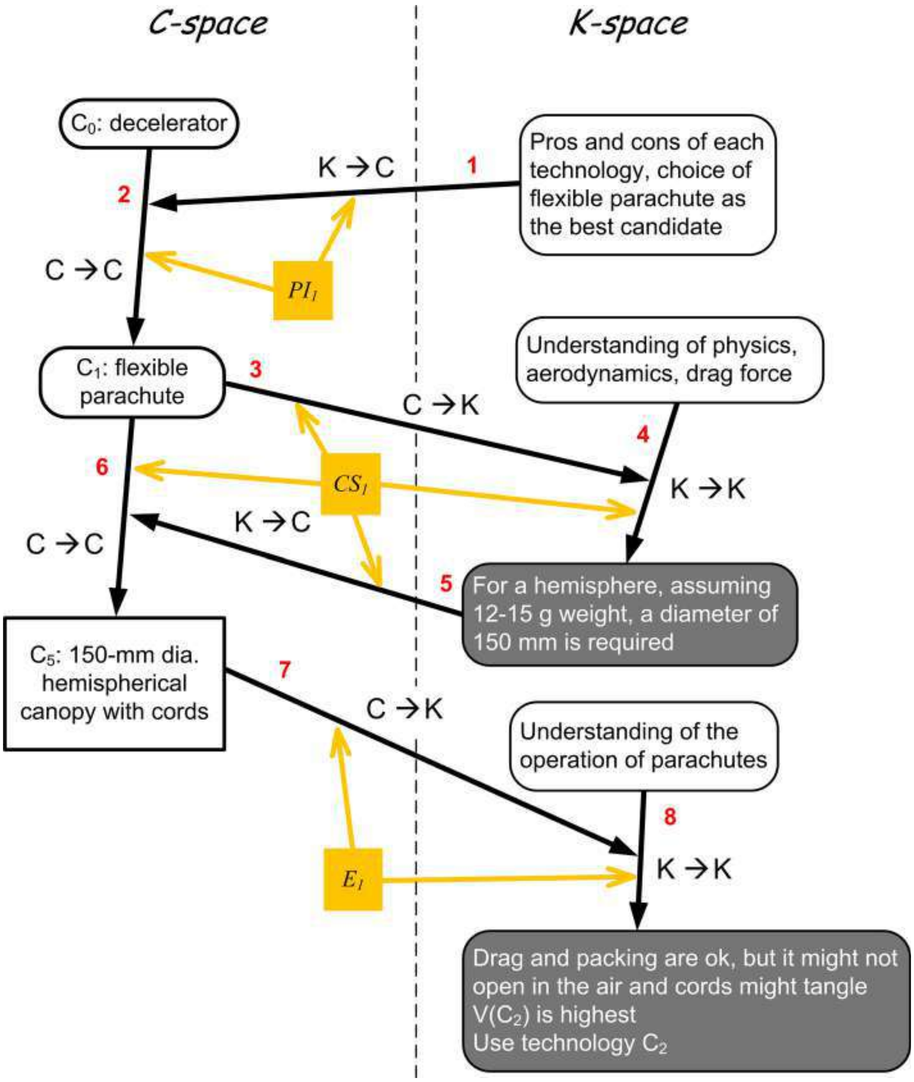


Fig. 12 C–K modeling of the first PI–CS–E cycle in the decelerator design example. The evaluation criteria are enriched thanks to analyzing the behavior of a configuration, by adding opening in the air and tangling of the cords. This results in the designers assigning the highest value to C_2*: rigid 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

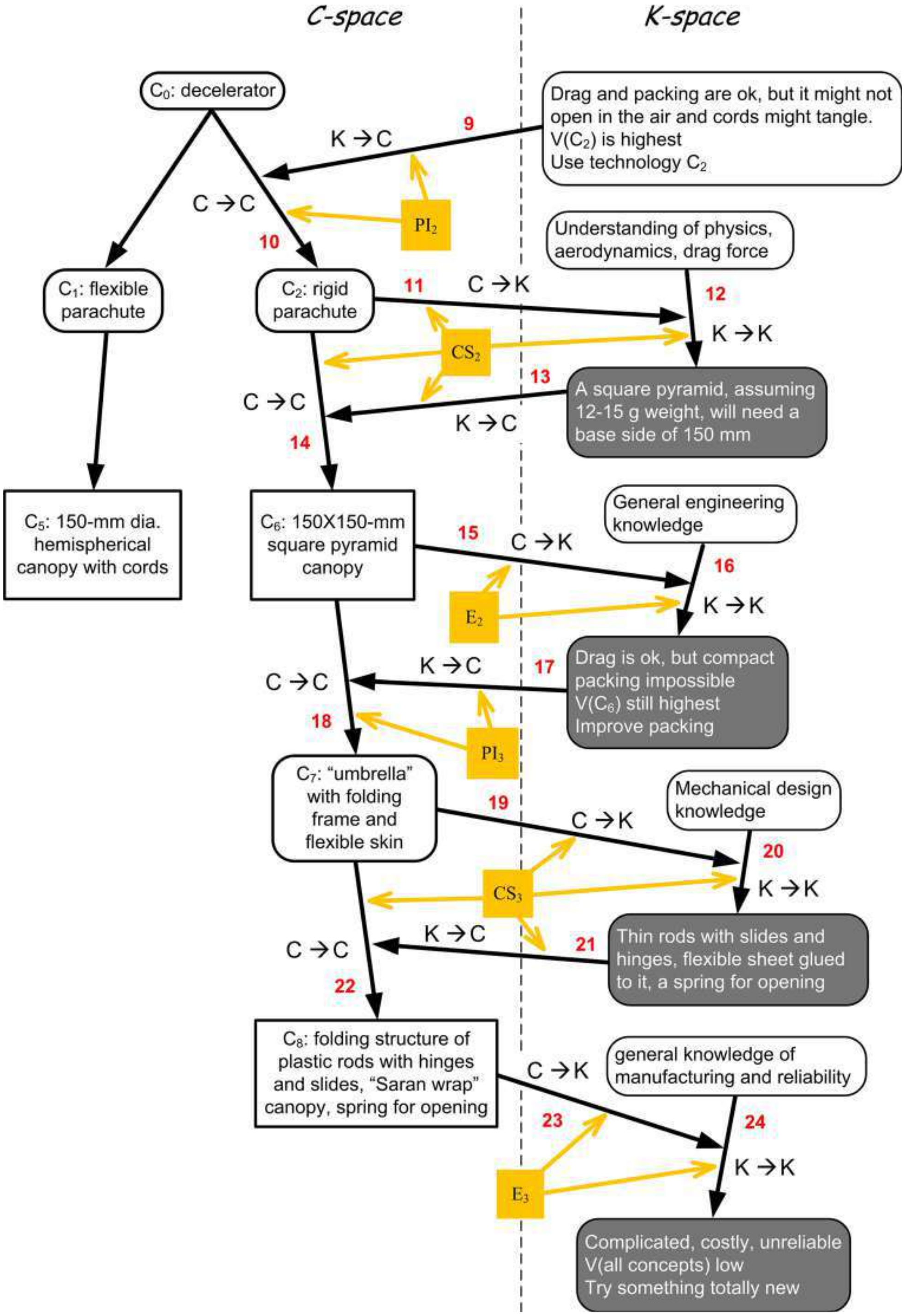


Fig. 13 The second and third PA cycles are added after pruning the flexible parachute branch. Both attempt to develop a concept with the rigid parachute technology. However, based on an updated set of evaluation criteria, the result is low values for all existing concepts and technologies

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

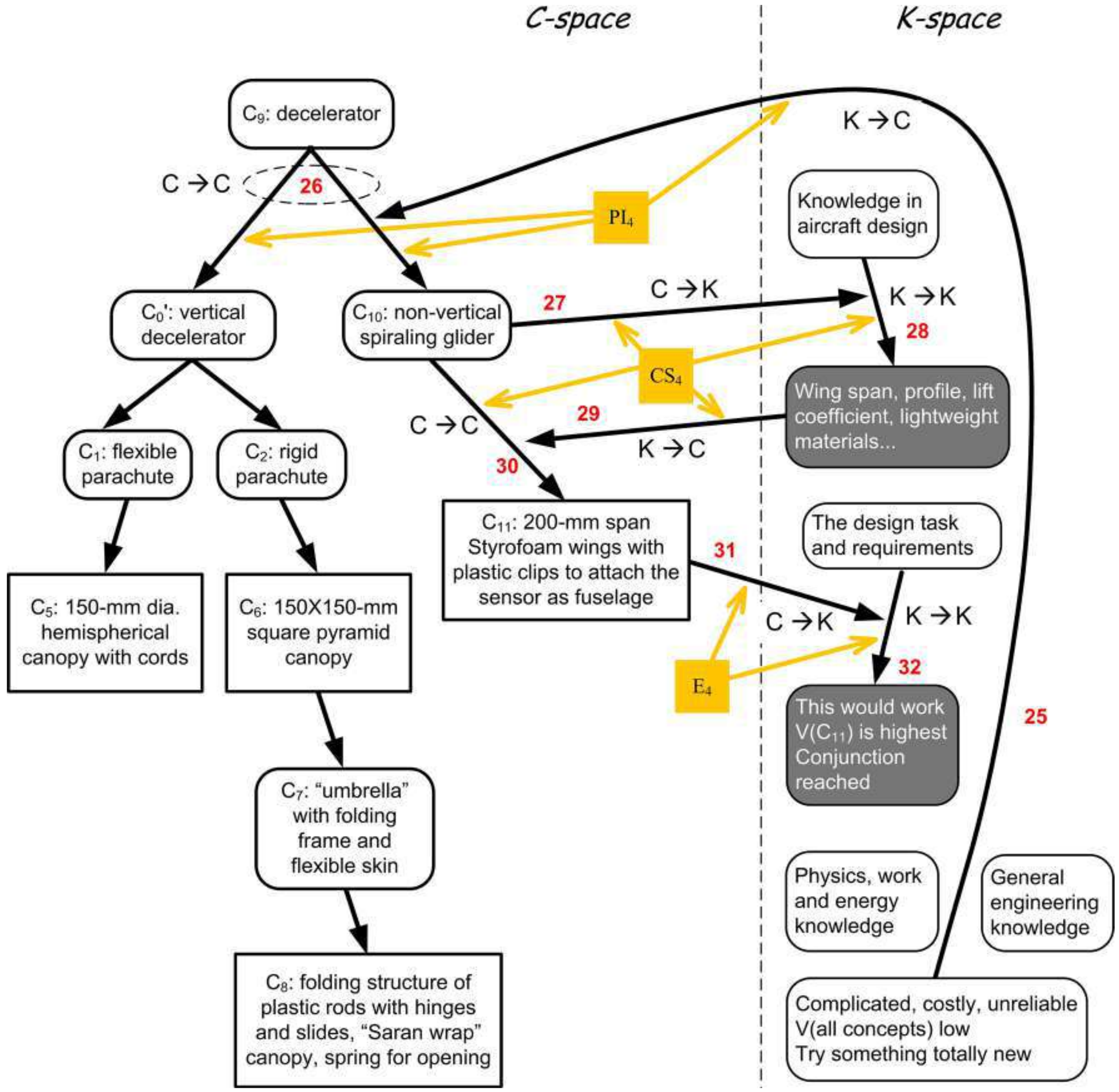


Fig. 14 C–K model of the fourth PI–CS–E cycle demonstrating a de-partition that leads to a conjunction for the root concept

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, $P_2,\ldots, P_m$) 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.

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ORIGINAL PAPER

Design theory and conceptual design: contrasting functional decomposition and morphology with parameter analysis

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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;

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[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

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[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

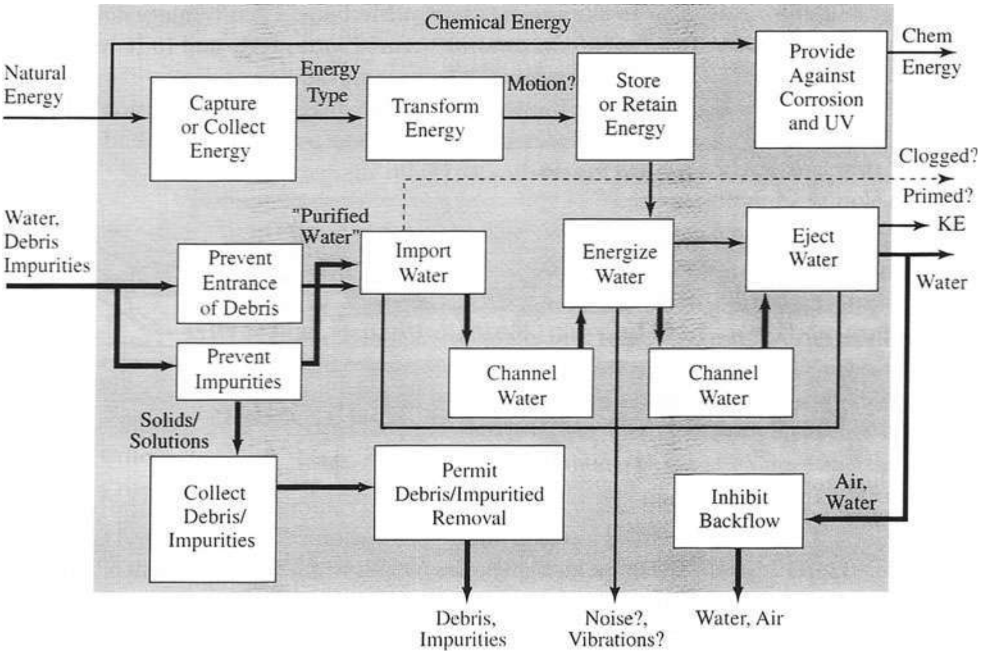
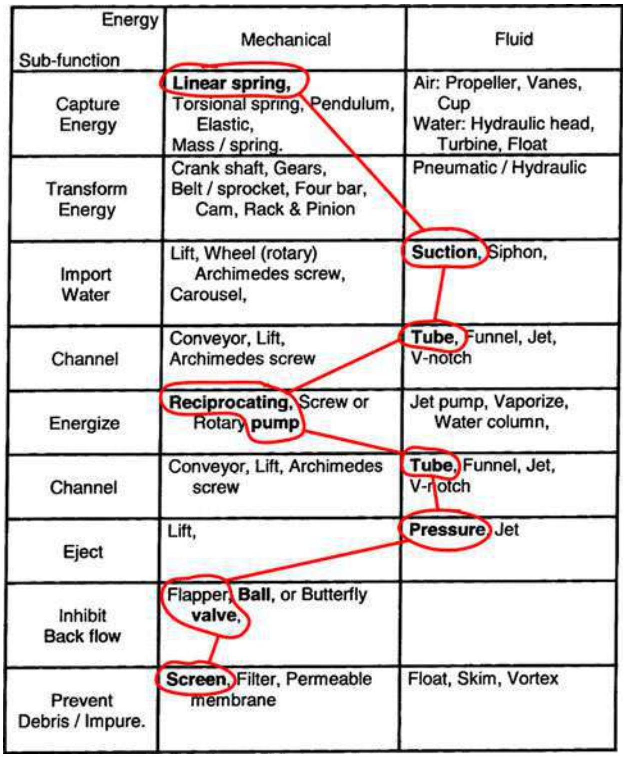


Fig. 1 The function structure for the bilge pump (Otto and Wood 2000)



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

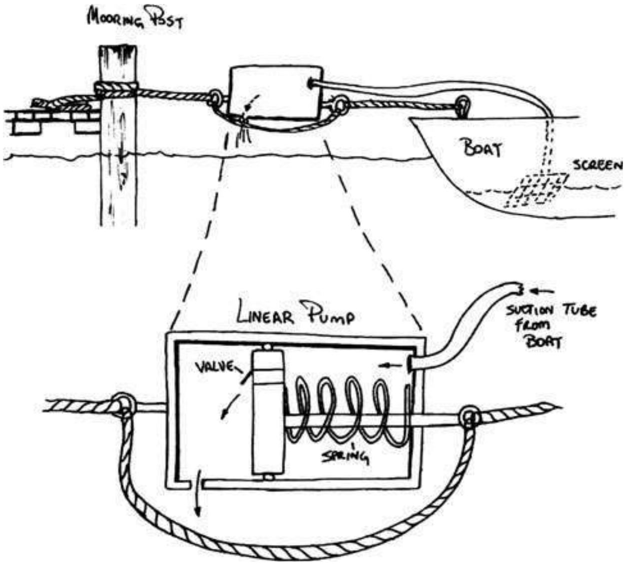


Fig. 3 One concept for the bilge pump that uses wave energy (Otto and Wood 2000)

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.

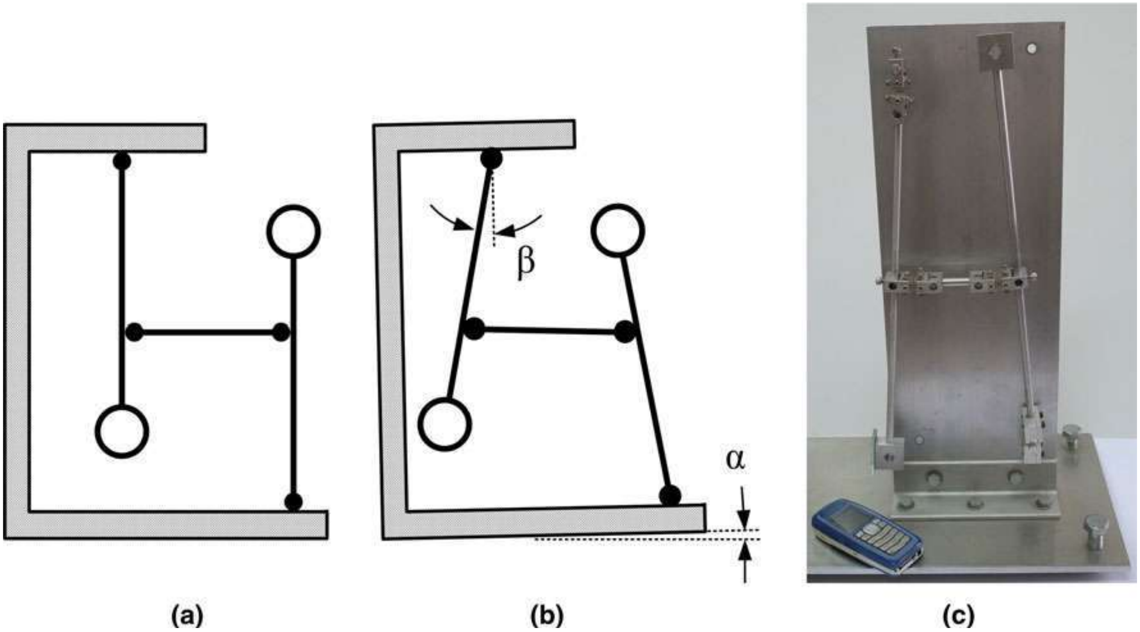


Fig. 4 **a** The tiltmeter with no input angle, and **b** an input angle α produces a response β where $\beta \gg \alpha$. The *large circles* are weights, *small solid circles* are hinges, and the *lines* represent stiff rods. **c** Photo of a working model of the tiltmeter

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 Δx 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.

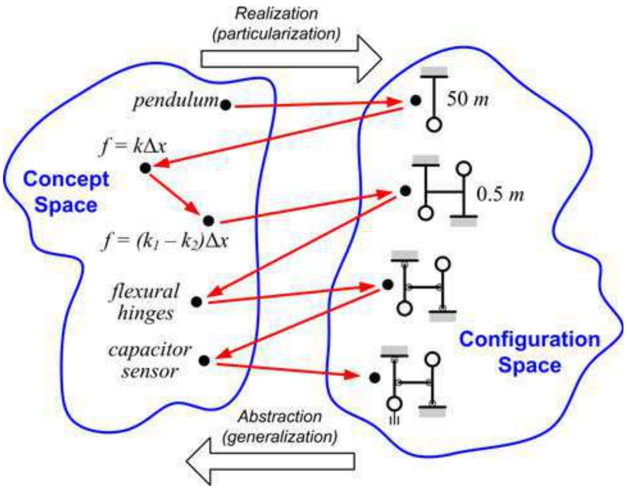


Fig. 5 A descriptive model of the conceptual design process of the tiltmeter as movements between concept and configuration spaces

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.

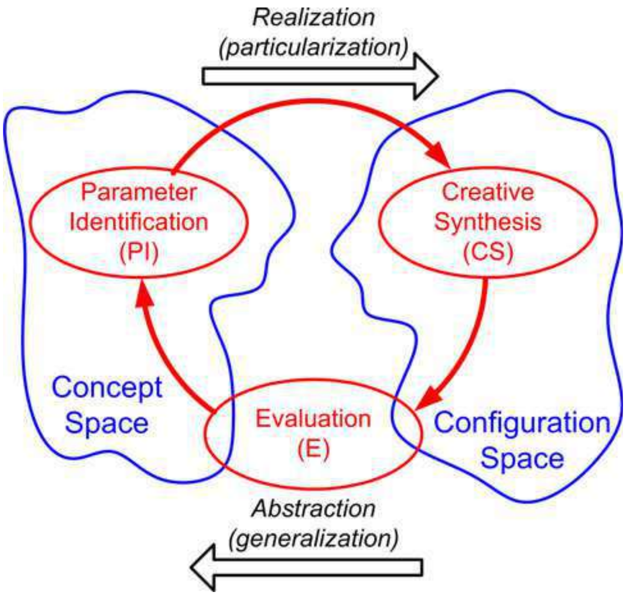


Fig. 6 The prescriptive model of conceptual design consists of repeatedly applying parameter identification (PI), creative synthesis (CS), and evaluation (E)

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 ~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.

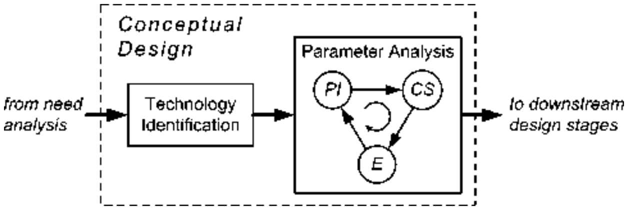


Fig. 7 A *technology identification* stage is added to the prescriptive model of parameter analysis

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.

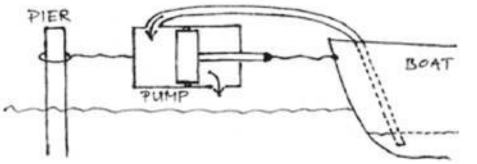
During the need analysis stage, some preliminary calculations showed that at $Re > 10^4$ (this Reynolds number corresponds to several tens of millimeters characteristic length and a velocity of 3 m/s), the drag coefficient C_D of a parachute shaped decelerator is about 2, so to balance a total weight of 12–15 g (10 g sensor plus 2–5 g assumed for the decelerator itself), the parachute's diameter will be ~ 150 mm. If the decelerator is a flat disk perpendicular to the flow, the C_D reduces to ~ 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.

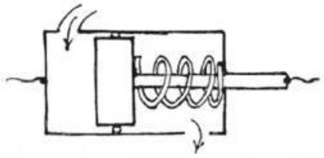
CS: A piston-in-cylinder type of reciprocating pump is attached by ropes between the pier and the boat. When the boat moves away from the pier, the piston creates suction on one side and pressure on the other, so the bilge water can be pumped.



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.

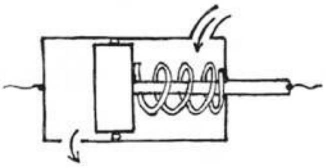
CS: A spring is added so that it's compressed when the boat moves away from the pier, and released on the way back.



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.

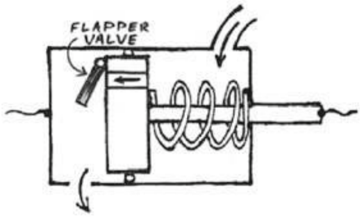
CS: The suction and ejection sides of the pump are reversed. When the boat moves away from the pier, the spring is compressed. When the boat moves towards the pier, all the spring's energy is used for pumping water. If the stroke of the piston is set to 50 mm and its diameter to 30 mm, then the volume 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.

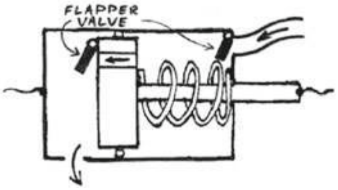
A functional decomposition and morphology process led student design teams to propose a conventional parachute (i.e., made of flexible material so that it can be folded for packing), "rigid parachute" (pyramid or conical shape, for example), and balloon filled with lighter-than-air gas (utilizing both 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.

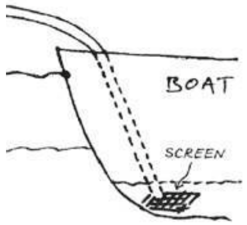
CS: Another flapper valve is added:



E: Debris/impurities may be pumped and clog the pump or interfere with the valves.

PI: Filter the water at the hose inlet.

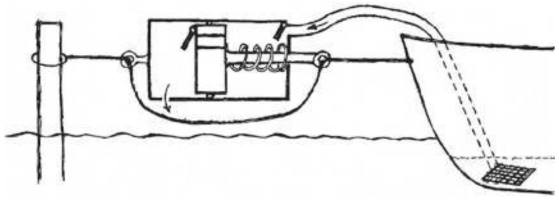
CS: A screen is added:



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.

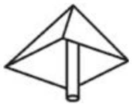
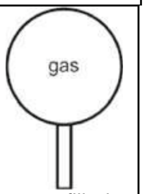
Subfunctions	Subconcepts		
Provide aerodynamic resistance	 *flexible parachute*	 *rigid parachute*	 *gas-filled balloon*
Allow compact packaging	*shapes enclosed in small volumes*	*nesting shapes*	*folding structures*

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

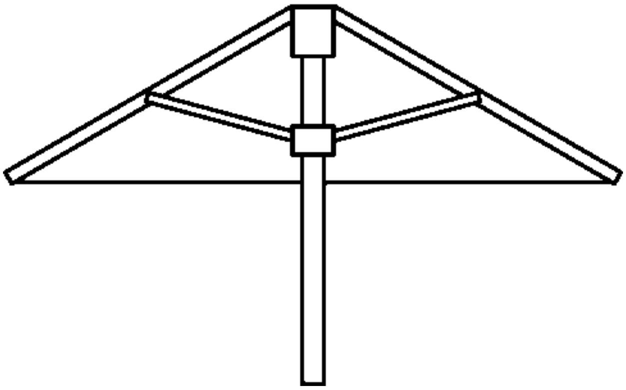


Fig. 10 Schematic of a proposed umbrella-type decelerator

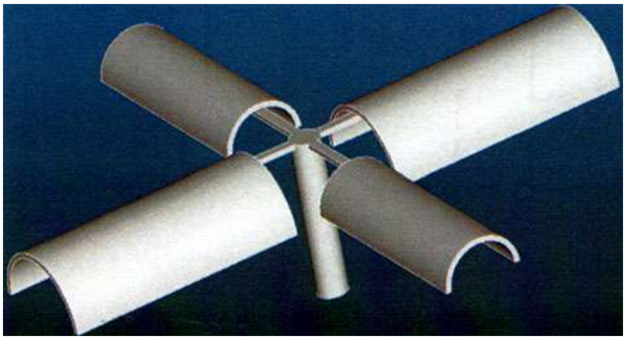


Fig. 11 A proposed design with two pairs of "wings" that can fold around the cylindrical sensor to allow compact packaging

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

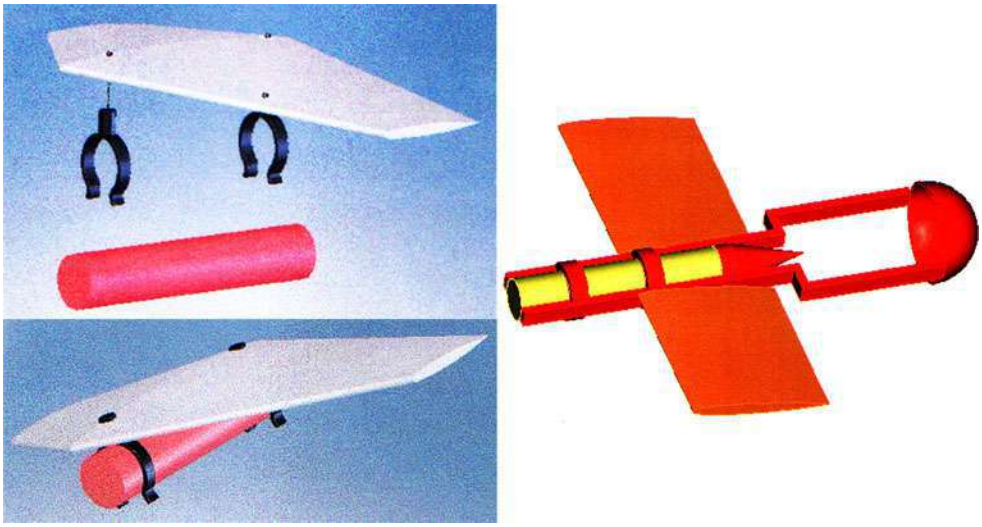


Fig. 12 Two "glider" designs showing the simplicity of the concept

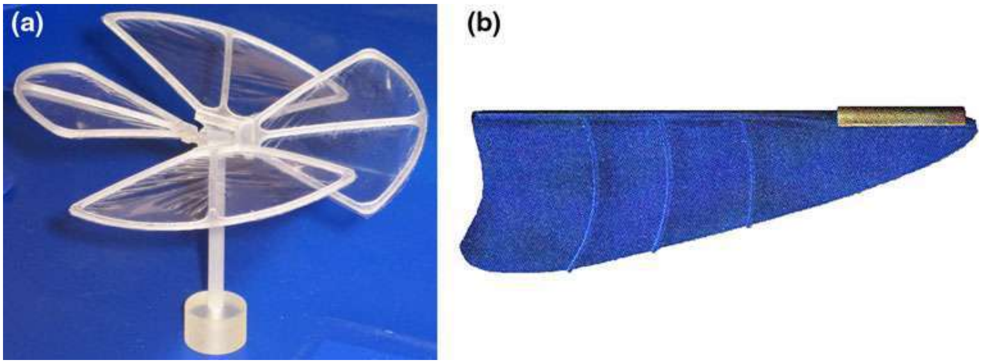


Fig. 13 **a** A prototype made for testing the "windmill" or "propeller" concept, **b** a model of rotating decelerator inspired by a winged Samara fruit

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

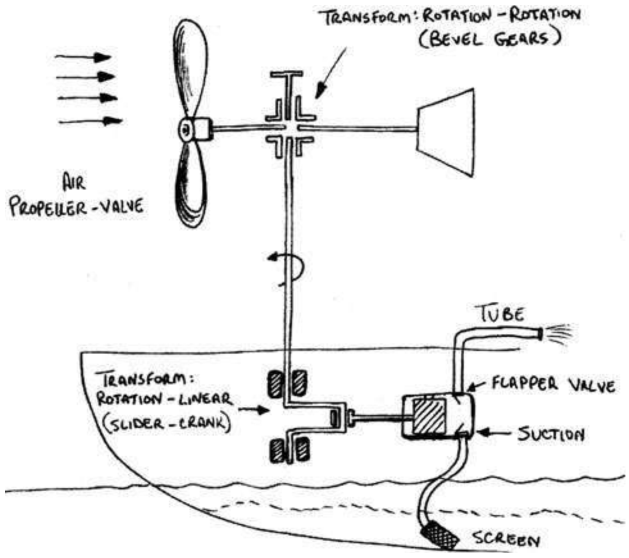


Fig. 14 One concept for the bilge pump that uses a wind turbine and reciprocating pump (Otto and Wood 2000)

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

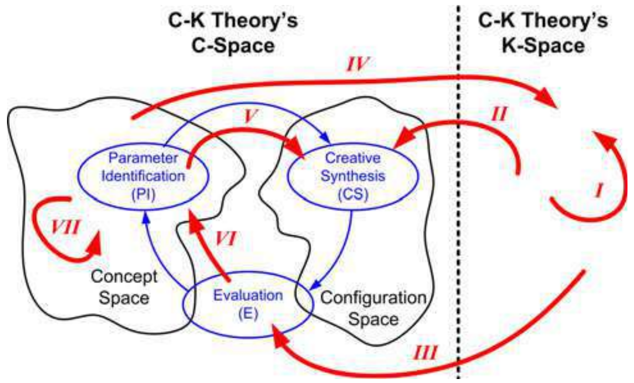


Fig. 15 Fitting together parameter analysis and C–K Theory. New meaning can sometimes be assigned to C–K's operators, depicted by the *arrows* with *Roman numerals*, as elaborated in the text

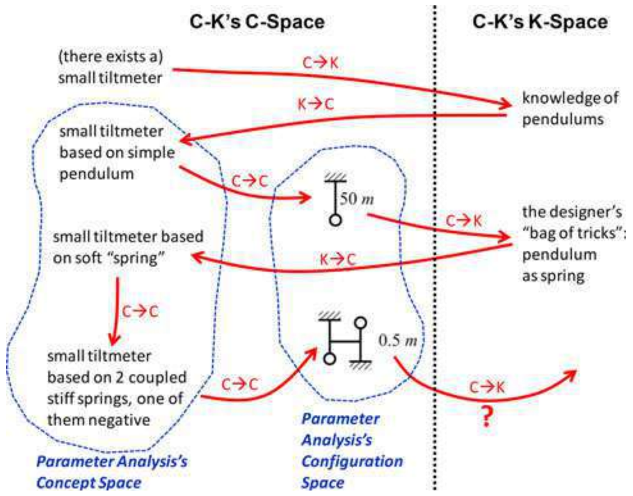


Fig. 16 The first few steps in the tiltmeter design process on a combined parameter analysis and C–K Theory diagram. All C–K's "concepts" are propositions of the form "there exists an object…" The *question mark* at the *bottom right* denotes checking the logical status of the last configuration, and 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

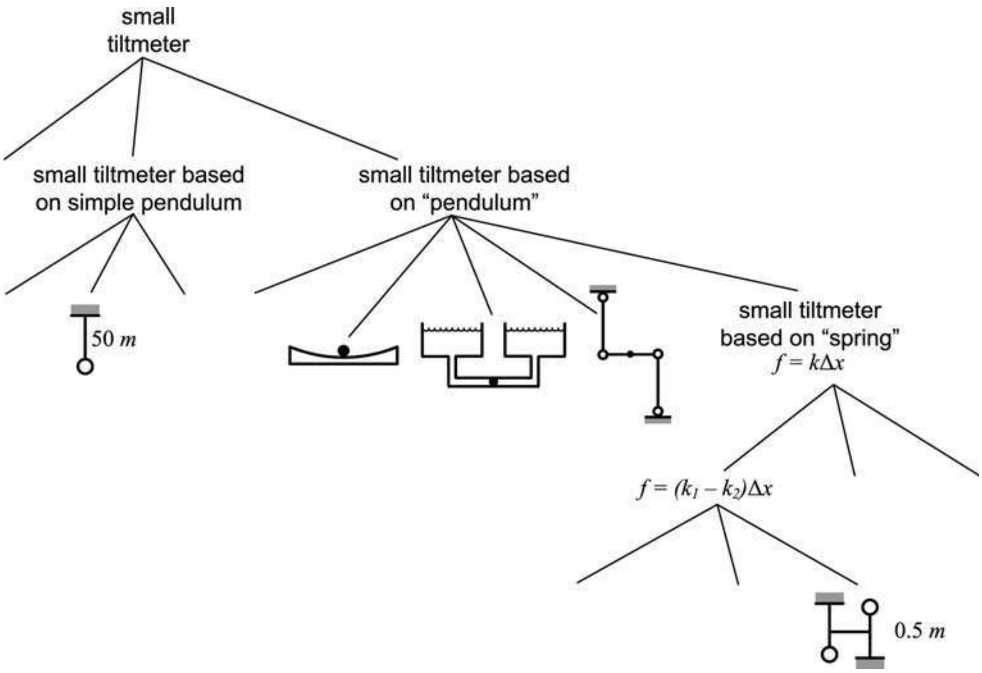


Fig. 17 Expansion of C-space by the first steps in the tiltmeter design example. Some of the concept sketches at the *center* of the diagram are unexplored possibilities mentioned in chapter 4 of Kroll et al. (2001)

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.

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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:

Reich, Y., & Subrahmanian, E. (2015). Designing PSI: an introduction to the PSI framework. In *DS 80-2 Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 2: Design Theory and Research Methodology Design Processes, Milan, Italy, 27-30.07. 15*.

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*.

TOWARDS PSI FRAMEWORK ADOPTION: CHARACTERIZATION OF DEVELOPMENT EFFORTS

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ABSTRACT

As systems and their development become increasingly complex, development efforts need to be planned. This planning involves proper tailoring of development procedures as a development process and selection of appropriate development methods.

One of the major setbacks in achieving such knowledgeable planning is the lack of common criteria for development efforts characterization. Typically, relevant past experience, applicability of development methods to different development situations, and procedures required as routine for product development in an organization are not clearly associated with the characteristics of development efforts. This makes the process planning difficult.

In this paper we present the motivation for development efforts characterization before turning to the Product-Social-Institutional framework (PSI framework) as a source of inspiration to approach such characterization holistically. We then suggest a method for efforts characterization that intermediates observable features with the more abstract concepts of the PSI framework. Finally, we demonstrate how such characterization can be beneficial in planning development efforts.

INTRODUCTION: MOTIVATION FOR DEVELOPMENT EFFORTS CHARACTERIZATION

As systems become increasingly complex, a multitude of tasks needs to be performed throughout the development lifecycle. These tasks are often communal in nature with respect to a specific line of products, a certain company and perhaps even a certain industry, and might require certain skills and perspectives to be incorporated into the development effort.

Various types of development efforts require different procedures and methods to be employed. For example, aviation regulations may require strict verification procedures to be incorporated into the development process of airborne equipment; vehicle regulations require integrating experiments into the automobile development plan in order to prove a vehicle's crashworthiness; drug development requires that the clinical phase is preceded by a pre-clinical phase; and typical hardware development includes environmental tests. The aforementioned procedures can sometimes be accomplished using various methods: airworthiness verification of software components can be claimed using a method of code reviews, code coverage analysis and/or various degrees of testing; and environmental testing of hardware can comprise testing under extreme conditions, full or limited functionality assurance under various conditions or testing only safety related aspects of the product.

Moreover, an organization, a project or development team can also have its own approach to development, embodying not only the aforementioned procedural and methodical requirements but also its goals, its capabilities and experience [1].

It is common practice to tailor development procedures from general guidelines and standards while planning a development effort. The "MIL-STD-498, Overview and Tailoring Guidebook" [2], for example, encourages such tailoring, and in fact, mentions it should be practiced as a continuous effort throughout the development project in order to achieve cost-effective development. Other reasons for tailoring, as specified by the aforementioned guidebook, are avoiding redundant costs, meeting shorter schedules and balancing near-term and long-term benefits. CMMI-DEV, a widespread model providing guidance for a development organization, requires tailoring to be performed in order to achieve “Maturity Level 3 – Defined” appraisal [3].

Corresponding with the proper planning of the development effort, learning from past experience is important in order to improve the way we develop systems. CMMI-DEV addresses this in its highest maturity level (Maturity Level 5: Optimizing), requiring that the “…organization continually improves its processes based on a quantitative understanding of its business objectives and performance needs.” This form of reflection is crucial to those who lead and orchestrate systems development throughout the development lifecycle (namely executives, project managers and system engineers).

While the need to tailor a development approach to a specific development effort and the desire to learn from past performance are valid, generalizing or deducing from one development effort to the other remains a challenge [1][4][5]. This challenge defers purposeful documentation and, eventually, transfer of development related know-hows and methods.

Process tailoring is acknowledged to require not only skills but also consistent characterization of development efforts [6]. However, due to a lack of standard characterization method for such efforts, a typical organization might find itself lost when trying to develop procedural best practices and tailoring guidelines [4]. These guidelines often rely on limited and partial criteria, such as budget, schedule or product type, and this is hardly holistic with respect to the effort in question. NASA, for example, approached its tailoring process for small satellite missions based on project costs and risk levels [7]. The IDF staff distinguishes between the development of systems primarily based on time to deliver (10/1 vs. 10/2 directives [8]) and on their allocated budget (which infers the level of the IDF staff oversight, in the 10/1 directive, for example). Cockburn suggests a framework to categorize development projects based on staff size and system criticality, and while he does recognize that more dimensions exist (and relates to them implicitly in his analysis as "project priorities" and "methodology designer's peculiarities"), he does not take into account important aspects such as regulations in his banking projects analysis, and only hints at technical maturity considerations [9]. Günther et al acknowledge the gap in efforts categorization and calls for future work to developing project characteristics and studying their interrelations and impact on the development process and methods [10].

Similarly, the applicability and effectiveness of emerging development methods in an organization or in a specific type of development effort is rightly and frequently questioned. Bass et al., for example, reflected on the conformance of Agile methods in a CMMI appraised organization [11]; whereas Ronkainen and Abrahamsson examined Agile methods applicability to embedded systems development, and identified applicability issues that arise from the effort's characteristics (specifically addressing the multiple development teams of such efforts and the required degree of formality) [12]. Moreover, in a more general, comparative analysis of Agile methods [13], Abrahamsson et al. recognized that most of these methods lack support of the project management perspective and called for such methods to clarify their range of applicability as a part of their definition.

In the following sections we suggest a characterization method for development efforts, inspired by the Product/Social/Institutional framework (the PSI framework), and demonstrate its holistic expression and application.

THE PSI FRAMEWORK

The PSI framework is a holistic approach to design, supporting the analysis of a design situation in three spaces – the Problem/Product space, the Social space and the Institutional space. A three-dimensional representation of each space exists as part of the PSI framework definition [14], and is depicted in Figure 1.

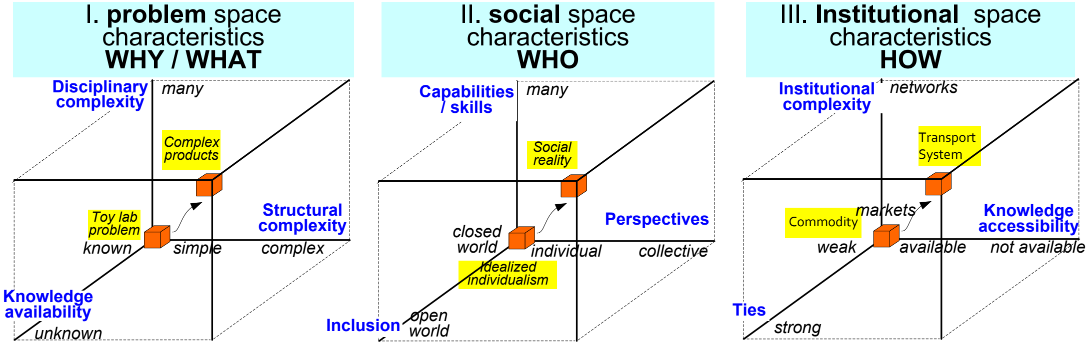

Figure 1: The PSI Spaces

The problem/product space characterizes what is being designed as a three dimensional space span by *disciplinary complexity*, *structural complexity* and *knowledge availability*. The social space characterizes the social entity that attempts the problem/product design; it has significant effect on the outcome of designing, and the PSI framework characterization defines its three dimensions as *number of perspectives*, *inclusion* and *capabilities/skills*. The institutional space characterizes the rules by which the participants of the design effort will operate throughout the effort; its three dimensions are *ties (social network)*, *knowledge accessibility* and *institutional structure complexity.*

Alignment between the PSI spaces is considered to be necessary in achieving project or organization success, as well as for explaining successes and failures [15]. The use of the PSI framework as an explanatory tool for failures and successes has been demonstrated in various cases [14][15]; nevertheless, much more benefit could be derived by creating a more detailed mapping, including quantitative, between projects and the framework.

The planning of system and product development efforts requires a holistic analysis of the design problem, and as such it corresponds directly with the PSI framework concepts. We will shortly demonstrate how the characterization of development efforts using the PSI framework concepts contributes to the efforts' proper analysis and planning.

AN INTERMEDIATE EFFORTS CHARACTERIZATION METHOD

Currently, the PSI dimensional association of a development effort is not directly measureable. The transition to the aforementioned, qualitative PSI spaces from real world metrics has yet to be defined, and is not straightforward, as it is not a one to one correspondence. This might hinder both practitioners and researchers from effectively adopting the PSI framework as an analysis tool.

In order to support effective analysis of development efforts using the concepts of the PSI framework, we developed an intermediate characterization method for describing such efforts. Instead of mapping the efforts directly into the PSI space (a procedure not yet defined), we tried to define a general development effort characterization method.

First, studying a multitude of system development projects, we identified several prominent characteristics of these efforts. *Project duration* is the estimated/required duration of the effort; *team size* quotes the number of people involved in the effort; *team structure* depicts the organizational method of the effort (e.g., integrated project team, matrix); *system/product maturity level estimation* reflects the maturity of the developed artifact (this is discussed shortly); *technical standards maturity level* estimates the maturity level of technical standards that need to be incorporated into the design; *regulation dependency level* marks the dependency of the development process on regulations; *number of engineering disciplines* identifies the number of engineering domains relevant to the development (e.g., system engineering, software engineering, mechanical engineering, quality engineering); *number of development skills* estimates the number of different skills required to perform the actual development (e.g., requirements engineering, algorithms development, software design, software coding, hardware design, system integration); *number of stakeholders* recognizes the number of major parties with interest in the developed system and its design (e.g., customer, end user, regulators, the organization itself and its employees); *number of subcontractors* identifies the quantity of subcontractors involved in the development by providing significant system component/s or design; *past experience* is the estimation of relevant know-how availability based on past experience within the organization or documented past experience elsewhere; *formality level* is the level of formality required from the development process, and is often reflected in artefacts produced throughout the development aside the system/product under development.

Most of these characteristics clearly correspond with the PSI space. The *number of stakeholders* characteristic, for example, can be expressed in the *number of perspectives* and *capabilities/skills* dimensions of PSI's Social space as well as across the Institutional space, and perhaps even in the Product space (especially *knowledge availability,* as the product might require implicitly requested features to satisfy the requirements of stakeholders other than the direct customer).

Next, we attempted classification of each project using these characteristics. This was not straightforward, and we approached this using a somewhat empirical approach. Specifically, in order to define the ordinal scale of each characteristic, we set to define meaningful bins for each characteristic (as in a histogram), according to both quantitative and qualitative measures. This was mostly done by using heuristics to establish the level and meaning represented by each bin. The binning of *team size* (which is in itself a quantitative measure) into three ordinal levels according to numeric thresholds is one such example. This yielded scales that may in fact be considered subjective/relative, organization-tailored scales. An organization which conducts development efforts of various sizes, for example, might benefit from defining its own binning levels for *team size*, in order to distinguish between large, medium and small sized projects.

In certain cases a more methodical approach was taken to define the ordinal scale of the characteristic. The *system/product maturity level estimation* scale, for example, was qualitatively assessed based on the adaptation of a scale similar to the Technology Readiness Level (TRL) scale. TRL scale is a popular scale used to estimate technology maturity, and has already been shown to be adaptable for estimating the maturity of hardware/subsystems and software [16].

The result of this approach was a set of characteristics, each with its own set of well-defined bins. This collection of characteristics and bins is depicted in Table 1.

The characteristics and the defined ordinal scales allowed us to map each project into a set of bins - a bin for each characteristic; which is, in fact, the manifest of the project's categorization. An illustrative characteristics map, representing several projects, is shown in Figure 2. In this figure, each effort categorization is visualized using a parallel coordinates graph [17], which intersects each characteristic (in the form of a vertical coordinate line) at its determined value. Project A, for example, is an effort with a duration ranked '2' (3-12 months), a high (ranked '3') regulation dependency, and its team structure is type '2' (matrix).

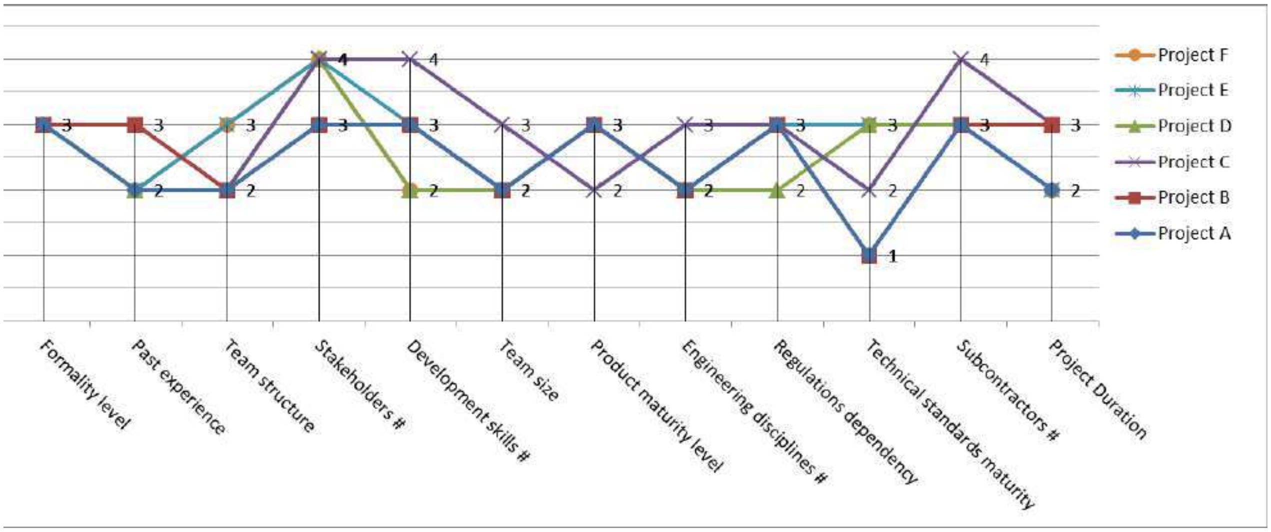

Figure 2: Projects categorization graphs using parallel coordinates

Table 1: Characteristics and their ordinal scales definitions

Bin number for characteristic	**1**	**2**	**3**	**4**	**5**
Project duration	Up to 3 months	3-12 months	over 12 months		
Team size	1-10 people	11-50 people	Over 50 people		
Team structure	Supervision (e.g. managing subcontractors in a turnkey project from a buyer's perspective)	Matrix	IPT	Hierarchal organization	
System/Product maturity level	TRL 2 equivalent / concept and/or application formulated	TRL 3 equivalent / Analytical and experimental critical function and/or characteristic proof of concept	TRL 4 Equivalent / Component and/or breadboard validation in laboratory environment	TRL 5 Equivalent / Component and/or breadboard validation in relevant environment	TRL 6 equivalent / System/subsystem model or prototype demonstration in a relevant environment
Technical standards maturity	Immature	High level guidance	Detailed guidance		
Regulation dependency level	None to low	Medium	High		
Number of engineering disciplines	Up to 2 disciplines	3-5 disciplines	Over 5 disciplines		
Number of development skill	Up to 2 disciplines	3-5 disciplines	5-10 disciplines	Over 10 disciplines	
Number of stakeholders	0 (self-initiative)	1	2	3	4
Number of subcontractors	None	1-3	3-10	Over 10	
Past experience	Low	Medium (similar)	High (more of the same)		
Formality level	Undocumented	Breathing documents	Managed	Highly formal	

INTERMEDIATE CHARACTERIZATION AS A PSI TOOL

In this section we illustrate how several of the proposed characteristics of development efforts correspond with the PSI framework, and how this correspondence allows our intermediate characterization to be employed as a PSI tool to support development effort planning. We start our PSI analysis with the *system maturity level* characteristic, and demonstrate how it corresponds with other characteristics as well as how they correspond with PSI framework concepts.

While typically considered a manifestation of the technical maturity of the product, *system maturity level* can also help in evaluating the institutional aspects of the development. The transition from a maturity level that establishes the product in a laboratory environment to one that validates the product in an operational environment is not merely a product maturation concern, but also one that typically includes procedural aspects - such as proof of serviceability and safety certification; and these correspond with some other suggested characteristics, e.g. *formality level*. Moreover, these PSI institutional space related aspects often require more perspectives to be incorporated into the development team, impacting the placement in the PSI social space (particularly on the *perspectives* dimension). An example of such reinforcement of the development team is the inclusion of a quality engineer, responsible for auditing the procedural aspects, and which, in our suggested, intermediate characterization, can be translated into an increase in the *Number of engineering disciplines*. This situation clearly demonstrates the meaning of alignment between the PSI spaces. A change in the Product space leads to a change in the Institutional space that in turn, impacts the Social space. Failure to align the spaces is likely to lead to failure.

Considering the projection of *system maturity level* on the PSI spaces can also support project planning tasks. The *system maturity level* - even when being interpreted as a technological/technical issue per se - can in fact be shown to be a driving incentive for social and institutional considerations of the project. If the maturity of the system under development is deemed low, then a possible way to align the development effort is by incorporating specializing subcontractors into the project team - a direct impact on the desired placement of the project in the social space of the PSI framework (specifically in the *inclusion* dimension), which using the aforementioned characteristics may take the form of increase in the *number of subcontractors*. Also, in such case, a lower *formality level* (less formal approach to the development) might be in order, encouraging creativity and trial and error by fostering strong institutional *ties*; and a suitable *team structure* (e.g., IPT, an Integrated project team) is advised.

Furthermore, a projects map, such as the one suggested in Figure 2, can be a useful tool in analyzing an organization according to PSI framework concepts. If, for example, the projects in Figure 2 are all associated with a specific organization, one might conclude that development efforts in this organization are all of formality level ‘3’ (“Managed”), and when prescribing development guidelines and processes this should be taken into account. Also, if a new project which requires a different level of formality is to be conducted, existing organizational procedures might not be suitable/optimal for such a project, and therefore reconsideration of existing practices is in order, set to achieve alignment (as in PSI spaces alignment). The case of Project G, which is quite atypical to the organization which performed Projects A-F, and is introduced as an additional graph to the aforementioned projects map in Figure 3, demonstrates the aforementioned analysis as well as the projects map usability as a visual, analysis support tool. The analysis in this case also encouraged examination of using an Agile development method, which was not previously used as it was found not in line with the organization's typical development procedures.

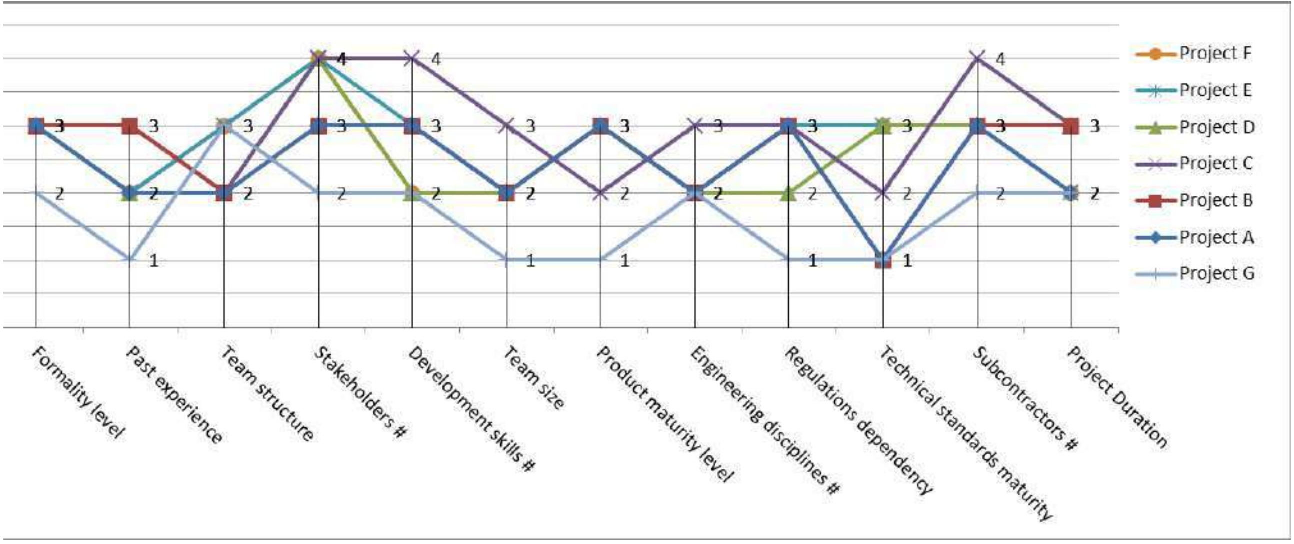

Figure 3: A projects map with Project G categorization graph

SUMMARY

There is a valid need for characterizing development efforts, as a basis for their better planning and researching. In this paper, we suggested a method of characterization for such efforts, by defining a set of common characteristics as well as suggesting an ordinal scale for each characteristic. Then, we demonstrated how analyzing development efforts characteristics in light of the PSI framework facilitates the PSI framework concepts adoption, and, as such, contributes to the understanding and planning of development efforts.

Further research is advised in order to establish and to elaborate the set of characteristics as well as to develop a more methodical assessment of the ordinal scales, which we approached empirically. We advise that such a method will support the definition of subjective/relative organization-tailored scales, as we suggested in our implementation. A standardized set of characteristics and characterization method is expected to provide a common ground for both the academic and the practical research of development efforts planning as well as of the applicability of development methods to various types of development efforts.

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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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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.

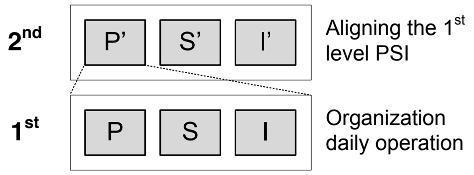

Figure 1. Aligning PSI spaces with a 2nd level PSI

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.

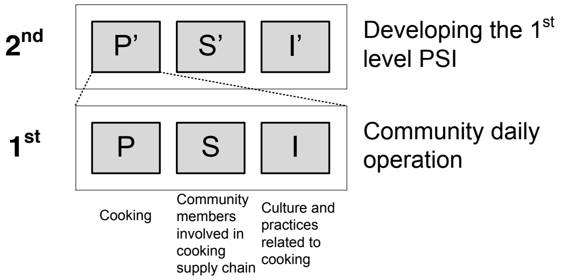

Figure 2. Modeling the cooking problem with a 2-level PSI framework

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.

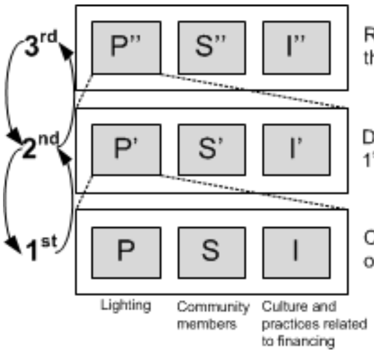

Figure 3. Modeling the SELCO case with a 2-level PSI framework

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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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.

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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

Paper ID #24777

Preliminary Findings From a Comparative Study of Two Bio-inspired Design Methods in a Second-year Engineering Curriculum

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Elizabeth Tafoya is a fourth year engineering student at James Madison University. In addition to engineering, Elizabeth also has a minor in geology. At JMU, she has participated in the Engineering Leadership Development Program to mentor first year engineering students and develop leadership skills. She has participated in bio-inspired design for Dr. J Nagel since the Spring of 2017 to further her interests in design processes.

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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*→*C*, *K*→*K*), conjunction which is testing a concept proposition to lead to new knowledge (*C*→*K)*, and disjunction which is a new concept being generated from existing knowledge (*K*→*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*→*C*), but they can also lead to the creation of new propositions in the *K* space (*C*→*K*). The combination of different pieces of knowledge and the addition of new discoveries expand the *K* space (*K*→*K*) and can result in new concepts (*K*→*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.

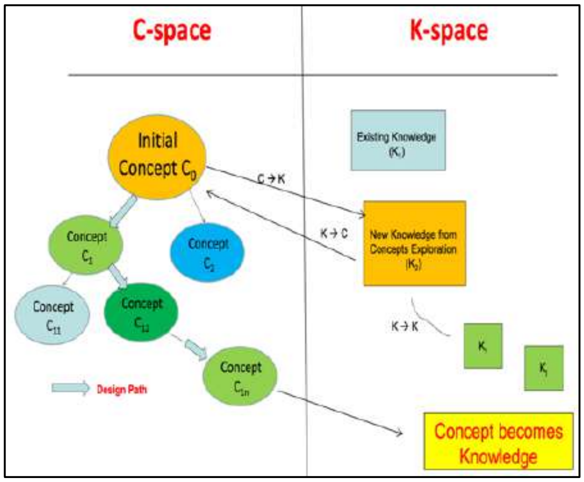


Figure 1: Concept-Knowledge Theory Framework

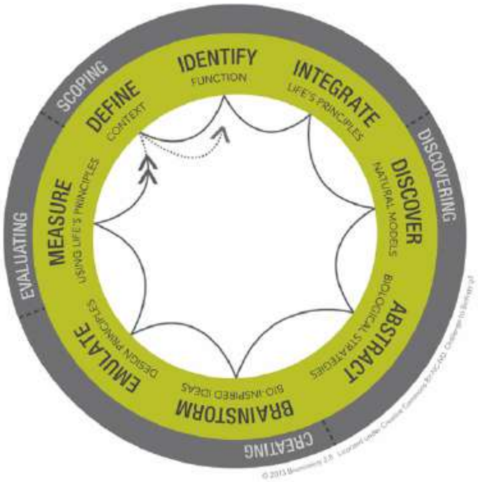


Figure 2: Biomimicry Institute Design Lens

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.

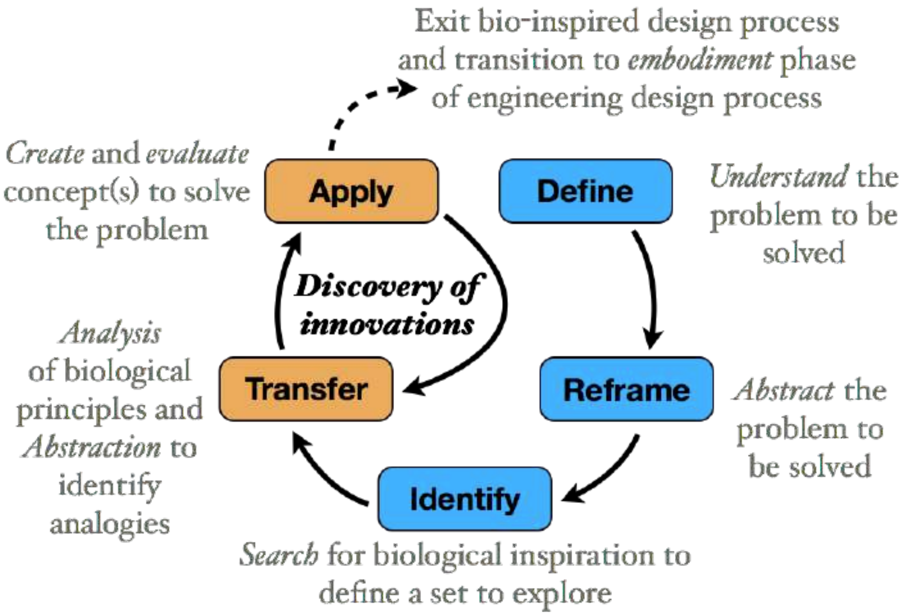


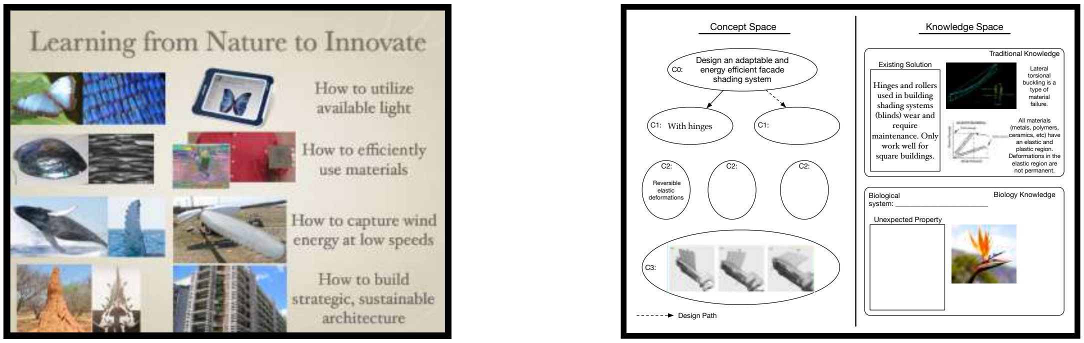
Figure 3: Bio-inspired Design Process

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

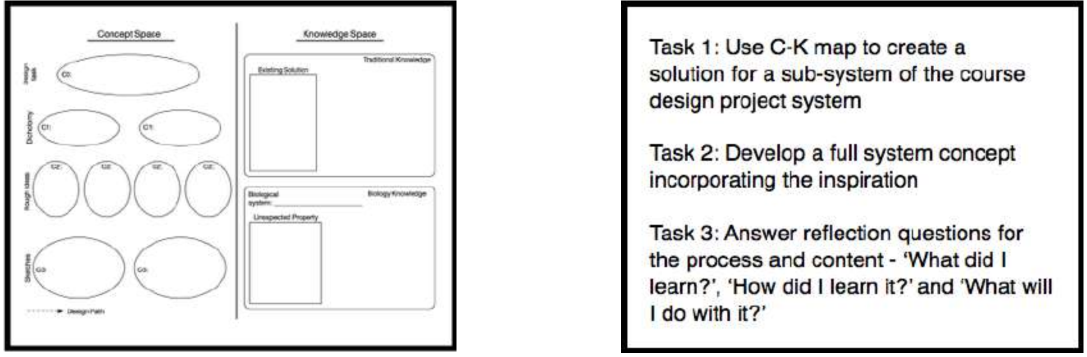
Concept Space	**Knowledge Space**
Posing questions to explore/answer	Analysis of existing knowledge (digging deeper)
Creation and partitioning of ideas	Drawing connections/linkages across knowledge
Documentation of a design path	Recognizing unexpected properties (opportunities)
Supports a problem-driven 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].



<u>Teaching Module:</u> exposure to breadth of inspiration and innovation and models the process

<u>Learning Activities:</u> In-class exercises that promote active learning and development of cross-domain linkages



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?'

<u>C-K Mapping Template:</u> visually structures the knowledge transfer process

<u>Assignment:</u> 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

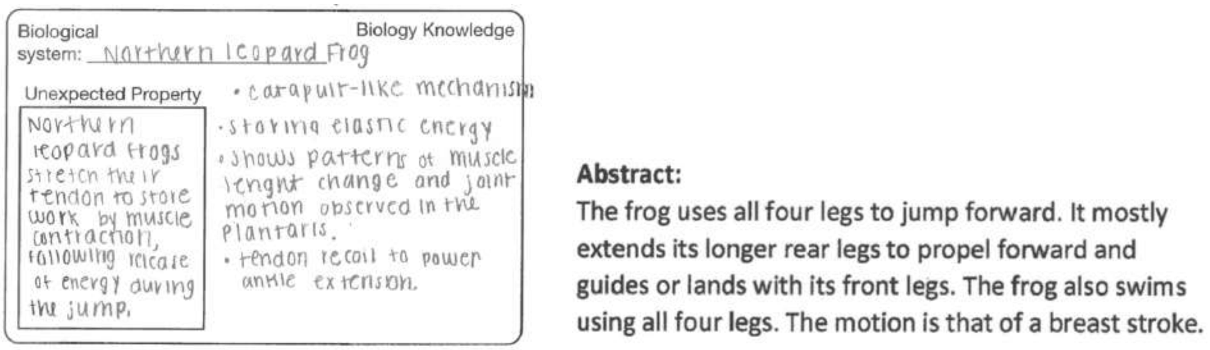
Both groups were tasked with creating a single propulsion sub-system concept for a human powered vehicle based on inspiration from the Northern Leopard Frog. The output from this task for the C-K group was a completed C-K map, and for the BI group a response to each of the eight steps of the Biomimicry 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	🟦	🟦	🟪	🟥	🟥



Biological system: Northern leopard Frog

Unexpected Property

Northern leopard frogs stretch their tendon to store work by muscle contraction, following release of energy during the jump.

Biology Knowledge

- catapult-like mechanism
- storing elastic energy
- Shows patterns of muscle lengnt change and joint motion observed in the plantaris.
- tendon recoil to power ankle extension.

Abstract:

The frog uses all four legs to jump forward. It mostly extends its longer rear legs to propel forward and guides or lands with its front legs. The frog also swims using all four legs. The motion is that of a breast stroke.

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

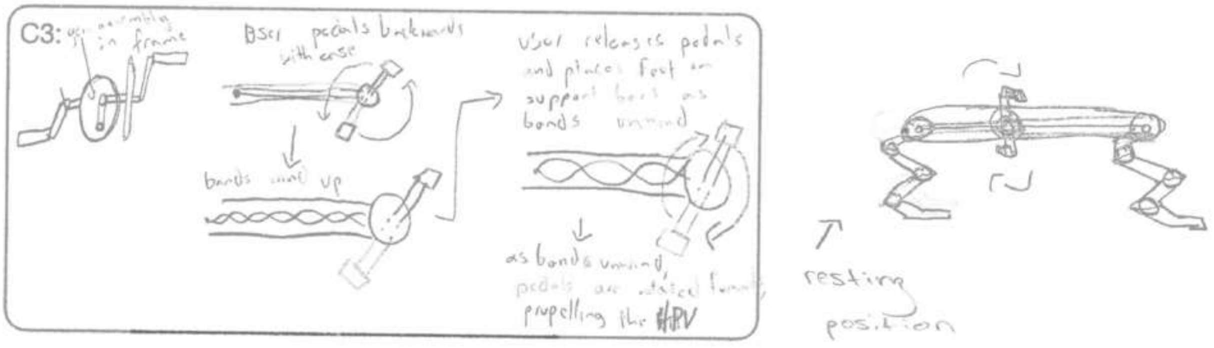


Figure 6: Example Student Work for Engineering Implementation Affinity Sort. Left: Elastic/Kinetic Energy Example. Right: Frog Motion Example.

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.

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Teaching bioinspired design using C–K theory

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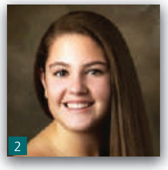
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The engineer of 2020 is expected to not only offer technical ingenuity but also adapt to a continuously evolving environment while being able to operate outside the narrow limits of one discipline and be ethically grounded in solving the complex problems 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]

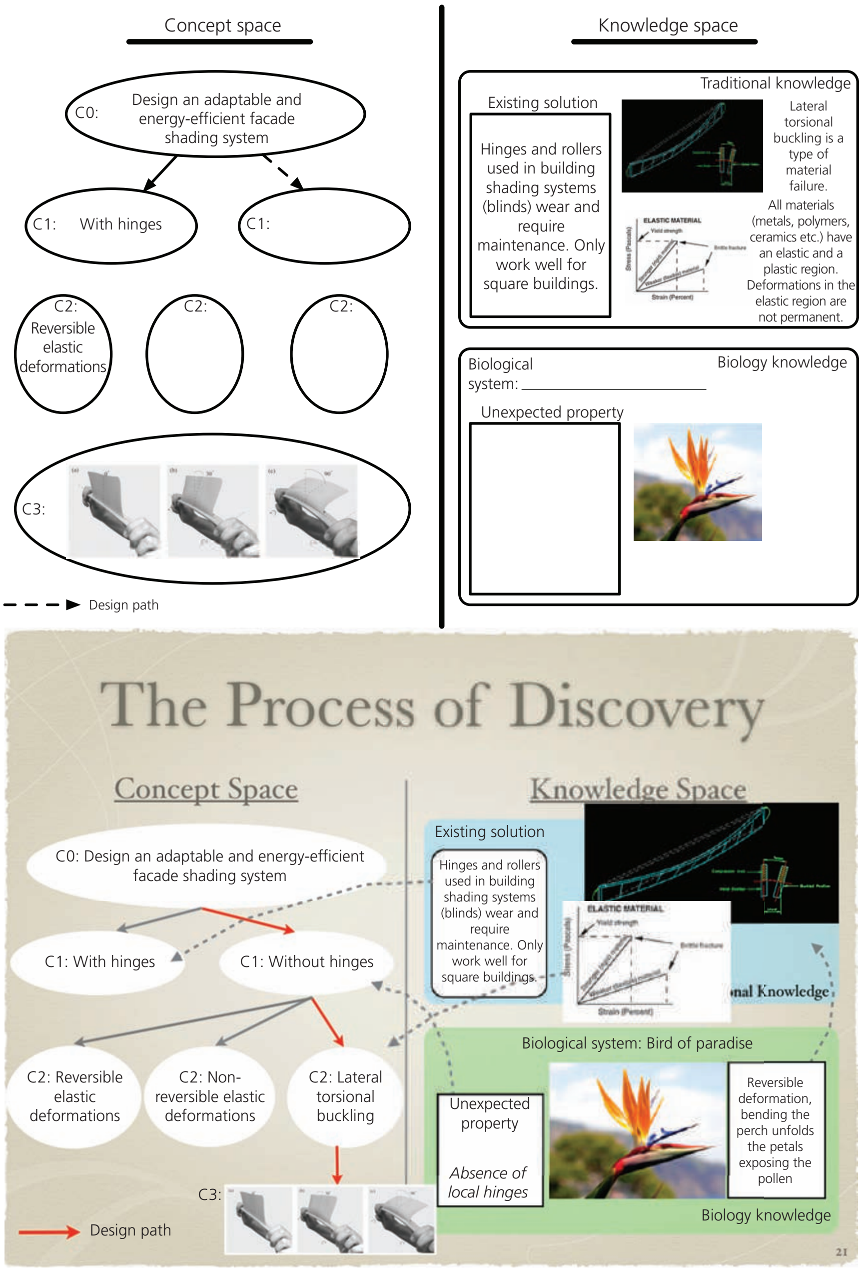
There are four operations allowed: expansion of each space ($C \rightarrow C$, $K \rightarrow K$); conjunction, meaning when a concept proposition is tested and leads to new knowledge ($C \rightarrow K$); and disjunction, meaning when a new concept is generated from existing knowledge ($K \rightarrow C$). 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



The Process of Discovery

Concept Space

C0: Design an adaptable and energy-efficient facade shading system

C1: With hinges

C1: Without hinges

C2: Reversible elastic deformations

C2: Non-reversible elastic deformations

C2: Lateral torsional buckling

C3:

Design path

Knowledge Space

Existing solution

Hinges and rollers used in building shading systems (blinds) wear and require maintenance. Only work well for square buildings.

nal Knowledge

Biological system: Bird of paradise

Unexpected property

Absence of local hinges

Reversible deformation, bending the perch unfolds the petals exposing the pollen

Biology knowledge

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.

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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

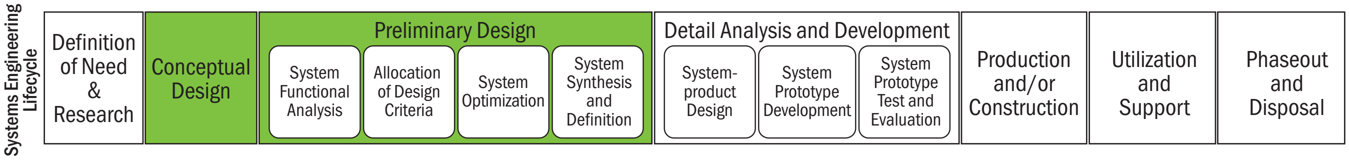

Figure 1. Some perceive BID to fit best with the early (highlighted) stages of the systems engineering lifecycle (adapted from Blanchard and Fabrycky 1998)

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

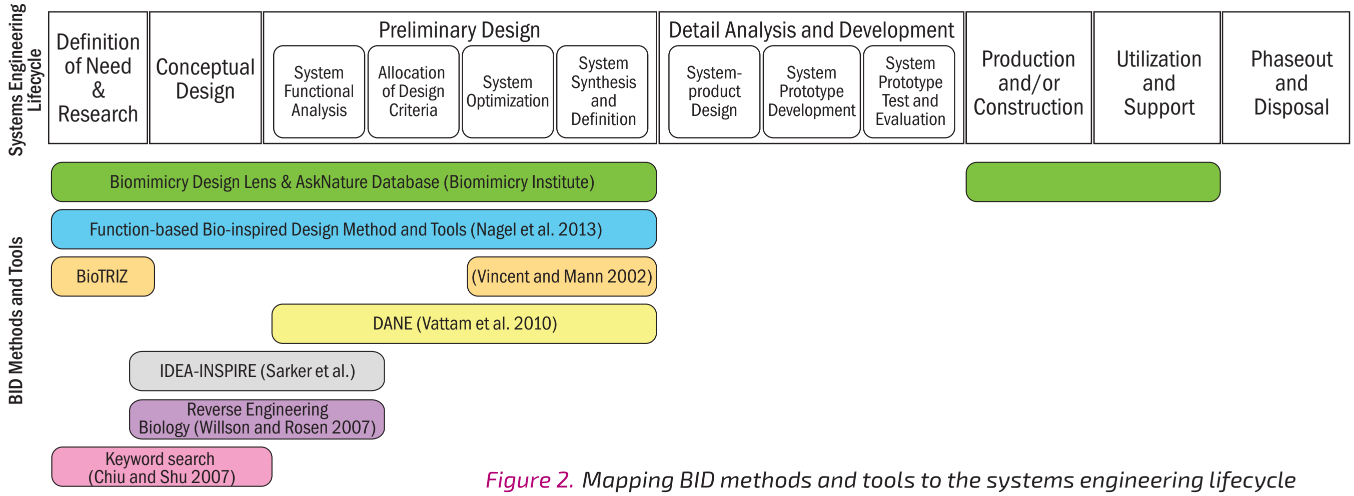

Figure 2. Mapping BID methods and tools to the systems engineering lifecycle (adapted from (Blanchard and Fabrycky 1998) reveals development opportunities

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 startups 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.

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

Day 3 – 1st Fev 2018			
Timetable	**Type of Course**	**Title Course**	**Speakers**
9:00 - 9:45	**Advanced topic / Paper discussion (3)**	Design creativity and innovation	Yukari Nagai
9:45 - 10:30	**Advanced topic / Paper discussion (4)**	Demonstration of fixation effect during generation of creative ideas from fundamental experimentation approach to applied experimentations.	Anaëlle Camarda
10:30 - 11:00	**Break**		
11:00 – 11:45	**Advanced topic / Paper discussion (5)**	Generative artificial intelligence	Akin Kazakçi
11:45 - 12:30	**Advanced topic / Paper discussion (6)**	Conjunctions of Design and Automated Search in Digital Innovation	Albrecht Fritzsche
12:30 - 14:00	**Lunch**		
14:00 – 15:00	**Master Class 3**		Benjamin Cabanes + Professorial College
15:00 – 16:00	**Publishing in design theory**	Room V115	Yoram Reich (RED) / Katharina Hölzle (CIM)

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.

Main References/ Further readings:

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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

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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.

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

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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.

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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.

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Keywords: American football; functional metrics; design decomposition; return on investment; axiomatic design

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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

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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 4th 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 4th 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.

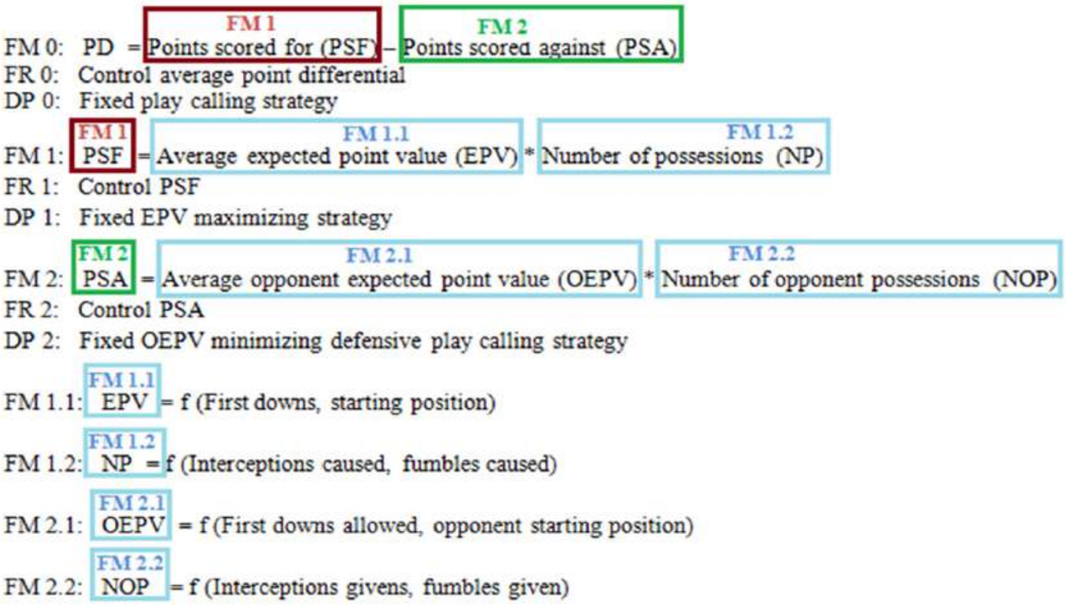
If the derivative over time of any of the FMs stagnates or trends in an undesirable direction, changes to improve the standard work are made. If this does not solve the problem then a new DP is chosen.

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].



FM 0: PD = Points scored for (PSF) – Points scored against (PSA)
FR 0: Control average point differential
DP 0: Fixed play calling strategy

FM 1: PSF = Average expected point value (EPV) * Number of possessions (NP)
FR 1: Control PSF
DP 1: Fixed EPV maximizing strategy

FM 2: PSA = Average opponent expected point value (OEPV) * Number of opponent possessions (NOP)
FR 2: Control PSA
DP 2: Fixed OEPV minimizing defensive play calling strategy

FM 1.1: EPV = f (First downs, starting position)

FM 1.2: NP = f (Interceptions caused, fumbles caused)

FM 2.1: OEPV = f (First downs allowed, opponent starting position)

FM 2.2: NOP = f (Interceptions givens, fumbles given)

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).

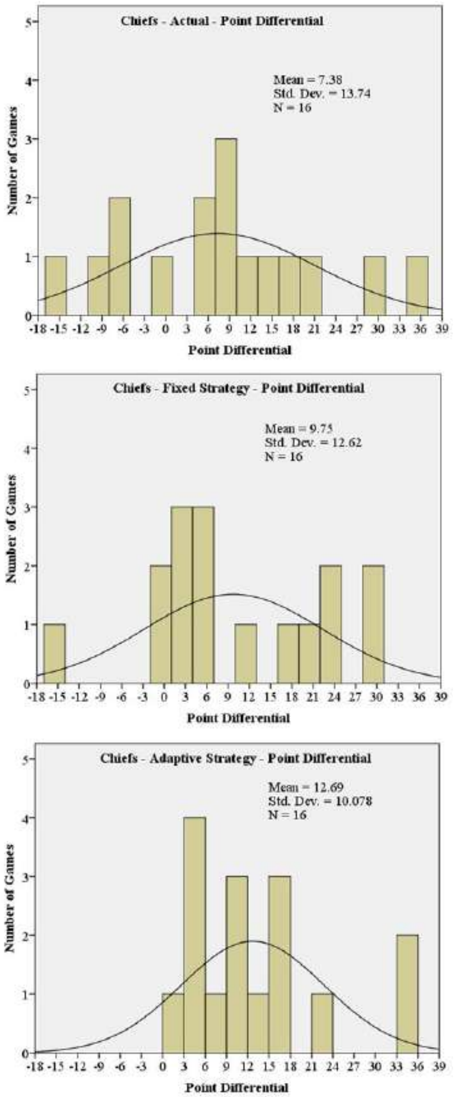


Fig. 2: Chiefs' means and standard deviations histograms

The equation for the field goal option (FGO) would be (1):

$$FGO\ EPV = \left((0.75*3) - (-0.64)\right) = 2.89 \quad (1)$$

The equation for the touchdown option (TDO) would be (2):

$$TDO\ EPV = \left((0.25*7) - (-1.3)\right) = 3.05 \quad (2)$$

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.

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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.

Keynote Address

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

Day 3 – 31 Jan 2019			
Timetable	**Type of Course**	**Title Course**	**Speakers**
9:00 - 9:45	**Advanced topic / Paper discussion (4)**	Demonstration of fixation effect during generation of creative ideas from fundamental experimentation approach to applied experimentations.	Anaëlle Camarda
9:45 - 10:30	**Advanced topic / Paper discussion (5)**	Generative artificial intelligence	Pascal Le Masson
10:30 - 11:00	**Break**		
11:00 – 11:45	**Advanced topic / Paper discussion (6)**	Conjunctions of Design and Automated Search in Digital Innovation	Albrecht Fritzsche
11:45 - 12:30	**Master Class 2**		Professorial College
12:30 - 14:00	**Lunch**		
14:00 – 15:00	**Master Class 3**		Professorial College
15:00 – 16:00	**Publishing in design theory**	Room V115	Yoram Reich (RED)

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Main research interests: psychology of creativity, neurosciences of creativity, design and creation.

Title of the Presentation:

Demonstration of fixation effect during generation of creative ideas from fundamental experimentation approach to applied experimentations.

Synopsis:

In this presentation we will discuss how the interaction between design theories and cognitive psychology, specially the experimental approach, help to understand why the generation of creative ideas can be blocked. In fact, it has been demonstrated many times that the ideation can be blocked and fixed on few paths of solutions that constrain creativity and prevent the exploration of more expansive and creative path of solutions.
After presenting the challenges of theoretical and methodological analyses of fixation effect in creativity, we will highlight why fixation effects biased the generativity according to cognitive models, and how it is possible to overcome it thanks to applied experimentations of new figures of leadership (in enterprises and classroom).

Main References/ Further readings:

Cassotti, M., Agogué, M., Camarda, A., Houde, O., & Borst, Gregoire. (2016). Inhibitory Control as a Core Process of Creative Problem Solving and Idea Generation from Childhood to Adulthood. New Directions for Child and Adolescent Development, 151, 61–72.

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.

Camarda, A., Agogué, M., Habib, M., Houdé, O., Borst, G. & Cassotti, M. Do we need cognitive control to be creative ? Evidence from a dual task paradigm. Psychology of aesthetics, creativity and the arts.

Ezzat, H., Camarda, A., Cassotti, M., Agogué, M., Houdé, O., Weil, B., & Le Masson, P. (2017) How minimal executive feedback influences creative idea generation. Plos one, 12(6) : e0180458.

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Do We Need Inhibitory Control to Be Creative? Evidence From a Dual-Task Paradigm

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The ability to inhibit common and dominant paths of solutions to a problem seems to be a critical process for generating creative ideas. However, previous behavioral studies have not systematically supported a positive relation between creativity and inhibitory control. Thus, the purpose of the present study was to determine the potential role of inhibitory control in creative idea generation. In Experiment 1, we used a dual-task paradigm to reduce participants' inhibitory control resources while performing a creative task. Participants were asked to propose as many creative solutions as possible to prevent a hen's egg from breaking when dropped from a height of 10 m under either interference or control conditions of a computerized version of the Color Word Stroop task. We found that inhibitory control load decreased creative capabilities in terms of fluidity and expansivity. To determine whether creative idea generation depends specifically on the ability to inhibit fixation effects, dual-task costs under a secondary working memory (WM) task were examined in a second experiment. The results revealed that WM load had no significant effect on creative ideation. Combined, these results confirmed that inhibitory control is a core process to overcoming fixation effects and generating original solutions in a creative task.

Keywords: creativity, inhibitory control, dual task

The ability to inhibit common and dominant paths of solutions to a problem seems to be critical to generating creative ideas (Cassotti, Agogué, Camarda, Houdé, & Borst, 2016a; Dietrich & Kanso, 2010). Although psychological and neuroimaging studies have both shown that inhibitory control is a core process involving numerous cognitive domains including reasoning (Houdé & Borst, 2014, 2015), decision-making (Crone & Dahl, 2012), and theory of mind (Bull, Phillips, & Conway, 2008), experimental studies to date have provided discrepant results regarding its role in creativity (Beaty, Silvia, Nusbaum, Jauk, & Benedek, 2014; Radel, Davranche, Fournier, & Dietrich, 2015). Although some studies report that generating creative solutions to a problem requires the inhibition of previous inappropriate ideas inducing fixation phenomena (see Cassotti et al., 2016a for a review), other studies suggest that inhibitory control hinders creative potential (Radel et al., 2015). Therefore, the present study aimed to clarify the potential role of inhibitory control in creative idea generation.

Early models of creativity assumed that creativity involved automatic processes such as loose associations and disinhibition (Eysenck, 1995; Martindale, 1999). According to this view, a lack of inhibitory control would be beneficial to fostering remote associations and intuitive thinking, leading to a stimulation of creative ideation. Empirical support of the assumption that poorer inhibitory ability facilitates creativity was provided by studies that showed that performances on inhibitory control tasks were negatively correlated to creative idea generation based on divergent thinking measures (Dorfman, Martindale, Gassimova, and Varta-

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nian, 2008; Kharkhurin, 2011; Lin & Lien, 2013a). The deleterious effect of inhibition on creativity was also supported by clinical studies of patients exhibiting inhibitory control deficits. For example, patients with attention-deficit/hyperactivity disorder (ADHD) and bipolar disorder provided more original associations and creative ideas in several creative tasks than healthy participants (Abraham, Windmann, Siefen, Daum, & Güntürkün, 2006; Healey & Rucklidge, 2006; Reverberi, Toraldo, D'Agostini, & Skrap, 2005; Russ, 2001; White & Shah, 2006). However, it should be noted that these patients rarely exhibited specific deficits in inhibitory control and that other investigations of patients with clinical disorders have provided discrepant results (see de Souza et al., 2014).

Additional evidence of the negative role of inhibitory control in creative thinking was provided by a study that asked participants to solve a creative task in which they had to generate unusual and creative uses of conventional objects, such as a brick, after performing inhibitory control tasks designed to exhaust their inhibitory control resources (Radel et al., 2015). In this study, the depletion of inhibitory control resources enhanced both the fluency and the originality of the ideas proposed by the participants, suggesting that "disinhibition" stimulates creativity.

In sharp contrast with the aforementioned studies, an increasing number of studies demonstrate a positive role of inhibitory control during idea generation. For example, a series of correlational studies have reported that inhibitory control performance, assessed using seminal inhibitory control tasks such as the Color Word Stroop task (Stroop, 1935), are positively related to various creative measures in adults (Beaty et al., 2014; Benedek, Franz, Heene, & Neubauer, 2012; Vartanian, 2009). In addition, industrial designers, who are experts in the creative exploration of alternative ways of thinking, exhibit not only higher divergent thinking ability but also higher inhibitory control efficiency compared with a control group of participants (Edl, Benedek, Papousek, Weiss, & Fink, 2014).

Some of the strongest evidence linking inhibitory control to creative thinking has been provided by neuroimaging studies that have shown a positive relationship between the ability to generate highly creative solutions to a problem and activation of specific prefrontal brain regions known to be implicated in executive function and inhibitory control in particular (Benedek et al., 2014; Dietrich & Kanso, 2010). For instance, activation within the inferior frontal gyrus—a brain region classically associated with inhibitory control (Aron, Robbins, & Poldrack, 2004, 2014; Houdé, Rossi, Lubin, & Joliot, 2010)—was positively related to the originality and appropriateness of ideas proposed by participants (Benedek et al., 2014). These results are in line with a meta-analysis of 45 functional magnetic resonance imaging (fMRI) studies on creative thinking, which showed that verbal and visuospatial creativity activated regions in the prefrontal network, including the anterior cingulate cortex, the inferior frontal gyri, and the middle frontal gyri (Boccia, Piccardi, Palermo, Nori, & Palmiero, 2015), three structures involved in conflict monitoring, inhibitory control, and working memory (WM), respectively. Thus, these three processes might have a fundamental role in creative ideation.

The hypothesis that inhibitory control is a core component of creative thinking is further supported by studies showing that previously acquired and existing knowledge or ideas can limit creative idea generation, leading to mental fixation (Storm & Angello, 2010; Storm & Patel, 2014). Although creative tasks require the exploration of new and original solutions, individuals tend to follow "the path of least resistance" and propose solutions based on common and undemanding design heuristics (Agogué, Poirel, Pineau, Houdé, & Cassotti, 2014b; Finke, Ward, & Smith, 1992). For example, when individuals must design methods to ensure that a hen's egg will not break when dropped from a height of 10 m (32 ft), the results revealed that adults fixed on a limited number of response categories based on the most accessible knowledge (Cassotti, Camarda, Poirel, Houdé, & Agogué, 2016b). Most of the solutions provided by the participants consisted of using an inert device to dampen the shock, protect the egg, or slow the fall (e.g., to slow the fall with a parachute), whereas more original categories of solutions that consisted of using a living object or modifying the natural properties of the egg (e.g., training a bird to catch the egg during the fall or freezing the egg before dropping it) were proposed less often by the participants. This "dark side" of fast and intuitive strategies to creatively solving a problem has led to the recent development of a dual process model of creative idea generation (Cassotti et al., 2016a). Following this view, creative idea generation requires the inhibition of dominant and common ideas within an intuitive and heuristic System 1 to explore new concepts with a generative type of reasoning within a deliberate and analytic System 2. Thus, to provide original ideas to problems such as "the egg task," one must first inhibit the intuitive and dominant paths to solutions that create fixation effects (referring to the first system) and then activate conceptual expansion reasoning (referring to the second system).

The discrepancies observed regarding the potential role of inhibitory control in creativity underscore the need to design experiments that systematically manipulate inhibitory control resources. Thus, in the present study, we aim to test whether inhibitory control is a critical process to generating multiple creative ideas by using a dual-task paradigm in which participants are asked to perform a creative task while performing an inhibitory control task. Dual-task methodology has proven useful for testing the involvement of executive resources in various domains such as reasoning (De Neys, 2006a, 2006b) and theory of mind (Bull, Phillips, & Conway, 2008). In the present study, the participants performed a verbal creativity task (i.e., the egg task, Agogué et al., 2014b; Cassotti et al., 2016b) in which they had to propose strategies to dropping a hen's egg from a height of 10 m without breaking it while performing no task (single task) or the congruent (control dual task) or incongruent (inhibition dual task) conditions of the Color Word Stroop task. Indeed, the Color Word Stroop task has been proven to be effective in reducing inhibitory control resources in dual-task paradigms in previous studies (e.g., Brown, Collier, & Night, 2013). In both conditions, the participants had to identify the ink colors of printed words that denoted different colors. In the congruent condition, the ink color was congruent with the color denoted by the words (e.g., *blue* printed in blue) whereas in the incongruent condition, the ink color was incongruent with the color denoted by the words (e.g., *blue* printed in red). Although both conditions require attentional resources, only the incongruent one requires inhibitory control to avoid reading the word meaning instead of the ink color.

It is important to note that this dual-task paradigm allows us to test contrasting predictions based on the contradictory theoretical views regarding the role of inhibitory control in creative thinking. We reasoned that if creative idea generation operates automatically and inhibitory control hinders creativity as suggested by Radel et al. (2015), then participants should be more creative (as indicated by better performance on the verbal creativity task) during the incongruent conditions of the Color Word Stroop task (i.e., inhibition dual task inducing a “disinhibition”) than participants performing the verbal creativity task under the single-task condition (i.e., in which inhibitory control resources are fully available). On the other hand, if creative idea generation draws on inhibitory control resources as suggested by the dual process approach (Cassotti et al., 2016a), then participants should be less creative (as indicated by lower performance on the verbal creativity task) during the incongruent conditions of the Color Word Stroop task than participants in the single-task condition. Finally, participants should be as creative during the congruent condition of the Color Word Stroop task (control dual task) as participants performing the verbal creativity task in the single-task condition.

Experiment 1

Method

Participants. Seventy-eight undergraduate students (55 females, 23 males, mean age = 20.49 years, range = 18–32 years, *SD* = 2.15) from Paris Descartes University participated in this study. All participants reported normal or corrected-to-normal vision. Each participant was randomly assigned to one of three experimental conditions: an inhibition dual-task condition (n = 28), a control dual-task condition (n = 24), or a single-task condition in which participants performed the creative task without a secondary task load (n = 26). The mean age did not differ between the three groups of participants assigned to the three conditions, $F(2, 75) = 1.97$, $p = .15$. All of the participants provided written consent and were tested in accordance with national and international norms governing the study of human research participants.

Design and procedure. Regardless of the experimental conditions, participants performed a creative task in which they were given 5 min to propose as many original solutions as possible to the following problem: “Ensure that a hen’s egg does not break when dropped from a height of 10 m” (Agogué et al., 2014a, 2014b; Agogué, Le Masson, Dalmasso, Houdé, & Cassotti, 2015; Cassotti et al., 2016a). Participants were instructed that there were no right or wrong answers and that they had to provide as many creative solutions to the problem as possible. It is critical to note that they were asked to provide their answer as soon as they came to their mind. To facilitate idea generation, the participants were seated alone in the experimental room, and they had to provide oral responses (recorded by a Dictaphone) to the egg task.

Participants’ responses were recorded throughout the task. To measure the effect of the dual-task condition on creativity in the egg task, we evaluated the participants’ answers based on three criteria: fluidity (the ability to generate many solutions, as measured by the number of solutions), flexibility (the ability to generate many categories of solutions), and expansivity (the ability to provide solutions outside of the fixation effect).

More specifically, to measure fluidity, we counted the number of solutions provided by the participants. When a participant proposed a solution that combined different proposals, we counted each proposal as one solution. With regard to flexibility, a trained rater assigned each solution to 1 of 54 solution categories (e.g., “using a pool of water on the floor to reduce the shock”). Subsequently, the number of applied solution categories was counted for each participant. We applied a well-validated measurement of originality on the egg task (i.e., expansivity) by studying the distribution of solutions in different categories. To do so, a trained rater assigned each solution given by the participant to 1 of 10 metacategories (Agogué et al., 2014a, 2014b, 2015; Cassotti et al., 2016b). On the basis of previous studies, three metacategories (i.e., reducing the shock, protecting the egg, and slowing the fall) met the qualifications for the fixation effect, whereas the other seven did not (e.g., using a living object and modifying the natural properties of the egg). To assess expansivity, we then counted the number of solutions provided that were outside of the fixation effect for each participant. It is critical to note that this qualitative measure of creativity is highly correlated with expert evaluations of the ideas using consensual assessment (Agogué et al., 2015; Amabile, Goldfarb, & Brackfleld, 1990).

In both dual-task conditions, the participants completed the egg task concurrently with either the congruent (i.e., the control dual-task condition) or the incongruent (i.e., the inhibition dual-task condition) version of the Color Word Stroop task. In both conditions, the participants were tested using laptop computers with a screen resolution of 1,366 × 768 pixels, (310×170 mm^2). Stimuli were presented using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA).

In the congruent and incongruent conditions of the Color Word Stroop task, participants were asked to identify the ink colors of printed words that denoted colors. In the incongruent condition, the ink color and the color meaning of the word were incongruent (e.g., *red* printed in green ink; see Figure 1); thus, the participants had to inhibit the meaning of the word (e.g., *red*) to correctly identify the ink color (e.g., green). In the congruent condition, inhibition was not required because the ink colors and the colors denoted by the words were congruent (e.g., *red* printed in red ink). Nine Stroop items were created by combining different color names (*red*, *green*, *blue*) with the three corresponding ink colors (RGB color codes 255;0;0, 0;255;0, and 0;0;255). Three items were congruent (e.g., *red* written in red) and six were incongruent (e.g., *red* written in blue). The words were presented on the screen in 24-point Courier New bold type on a black background. In both conditions, participants provided their responses by pressing one of three keyboard buttons associated with the three possible ink colors (i.e., red, green, and blue). Participants were asked to answer as quickly as possible while maintaining high accuracy. Therefore, participants provided oral responses to the egg task and concurrently provided motor responses to the Stroop items by pressing one of three keyboard buttons. Each condition involved 141 experimental trials preceded by a training session of 57 randomly ordered trials. To control that each participant performed the same number of trials in each condition, each item (i.e., incongruent stimuli for the inhibition dual-task condition and congruent stimuli for the control dual-task condition) remained on the screen during 1,300 msec and was preceded by a white fixation cross displayed on a black background for 330 msec. After each trial, they received feedback on the accuracy of their responses for 500 msec. In each trial of the training session, a colored dot was

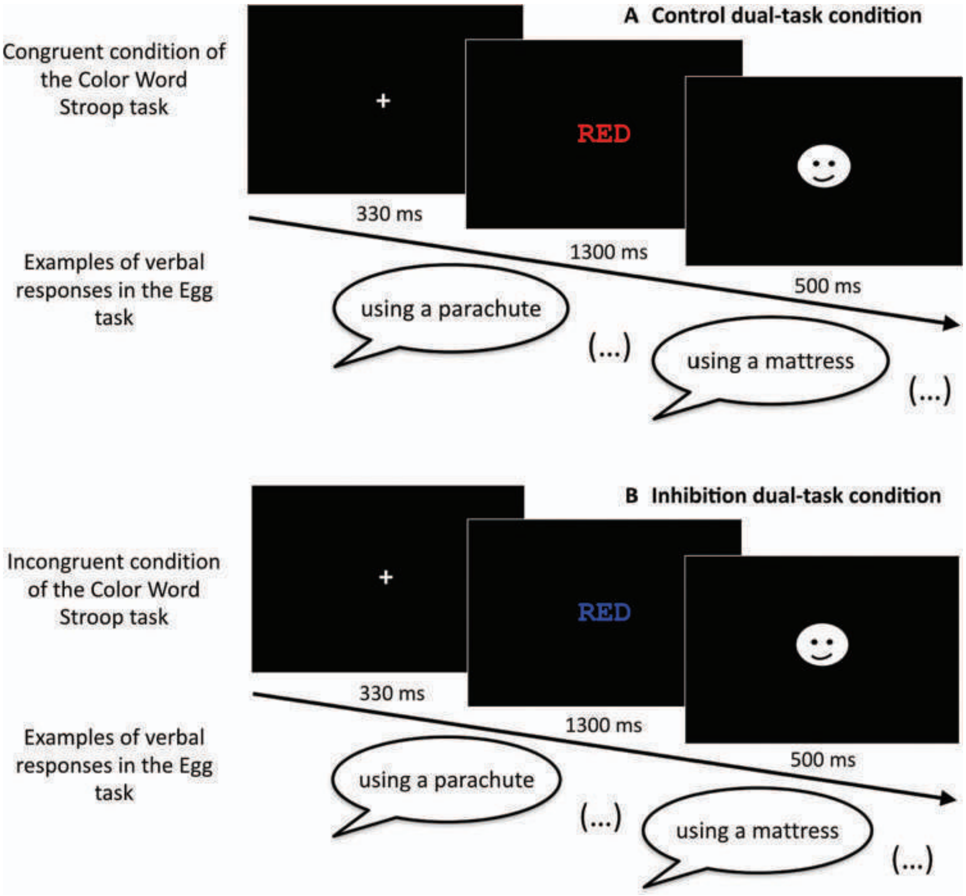

Figure 1. (A) Example of trials in the congruent (i.e., the control dual-task condition) and (B) the incongruent (i.e., the inhibition dual-task condition) Color Word Stroop task conditions. The text bubbles are examples of verbal responses provided by the participants in the egg task that could occur at any moment during both the control dual-task and the inhibition dual-task conditions. See the online article for the color version of this figure.

displayed in the center of the screen, and the participants pressed the corresponding response button as quickly as possible. The training session aimed to automatize the participants' motor response. Finally, to ensure that the participants actually performed the Color Word Stroop task while generating creative ideas, we excluded participants with a performance in the congruent or incongruent conditions of the Color Word Stroop task that was lower than 2 median absolute deviations (MADs) from the median of the group. Thus, two participants from the inhibition dual-task condition and one participant from the control dual-task condition were excluded from the subsequent analysis.

Results

The fluidity, flexibility, and expansivity scores were submitted to one-way analyses of variance (ANOVAs) with condition as the between-subjects factor (inhibition dual-task condition, control dual-task condition, and single-task condition), and we used η_p^2 and Cohen's *d* to assess the effect size. Correlation analysis between our different measures of creativity revealed that fluidity and flexibility scores were highly correlated, $r(73) = .82$, $p < .01$. In addition, a significant correlation was found between fluidity and expansivity scores, $r(73) = .61$, $p < .01$. Given that the correlation between the fluidity and flexibility scores was higher than .80, we have restricted the data analysis to the fluidity and expansivity scores to avoid redundancy.

Regarding fluidity, the one-way ANOVA revealed a main effect of condition, $F(2, 72) = 3.52$, $p = .03$, $\eta_p^2 = .09$ (see Figure 2A). More specifically, the planned contrasts revealed that the participants in the inhibition dual-task condition ($M = 7.04$, $SD = 5.17$) proposed fewer solutions than those in the single-task ($M = 10.69$, $SD = 4.91$), $F(1, 72) = 5.75$, $p = .02$, $d = .72$, and the control dual-task condition ($M = 10.43$, $SD = 6.4$), $F(1, 72) = 4.66$, $p = .03$, $d = .58$. In addition, the results showed no significant difference between the participants in the control dual-task condition ($M = 10.43$, $SD = 6.40$) and those in the single-task condition in terms of fluidity ($M = 10.69$, $SD = 4.91$), $F(1, 72) < 1$, $d = .05$. Regarding expansivity, the main effect of condition tended to reach significance, $F(2, 72) = 2.56$, $p = .08$, $\eta_p^2 = .07$. Given our theory-driven hypothesis, we examined the differences between the three conditions using independent *t* tests. The results showed that participants in the inhibition dual-task condition provided fewer responses outside of the fixation paths (i.e., expansivity,

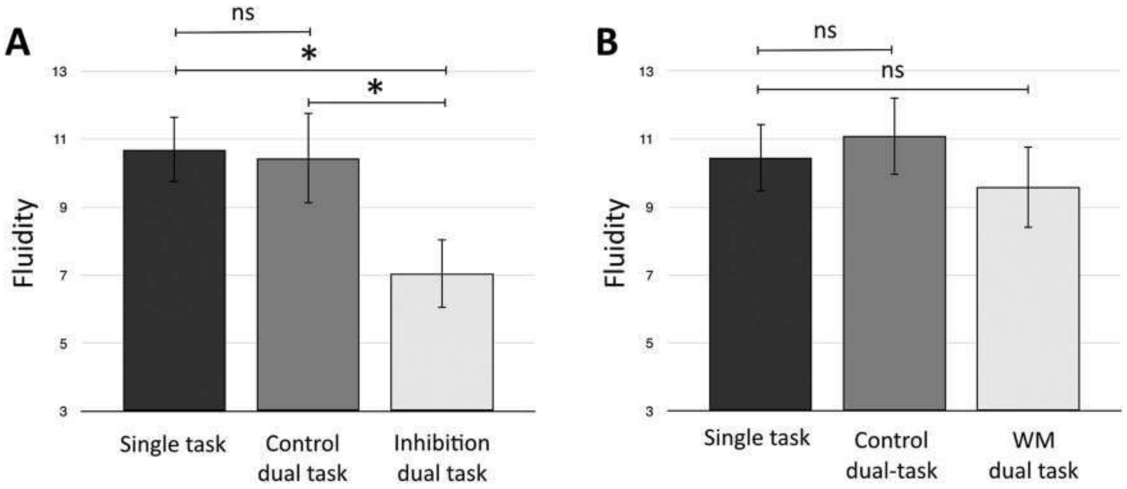

Figure 2. (A) Scores of fluidity according to the experimental conditions in Experiment 1. (B) Scores of fluidity according to the experimental conditions in Experiment 2.

M = 1.73, SD = 1.87) than those in the single-task condition (M = 3.12, SD = 2.64), $t(50) = 2.18$, $p = .03$, $d = .61$. In addition, the results showed no significant differences between the participants in the single-task condition and those in the control dual-task condition (M = 2.82, SD = 2.38), $t(57) = 0.40$, $p = .69$.

Discussion

Using a dual-task paradigm that manipulated the availability of inhibitory control resources during a creative idea generation task, we observed that inhibitory control load decreased creative capabilities in terms of fluidity and expansivity. In sharp contrast with the idea that disinhibition stimulates creativity (Radel et al., 2015) and in line with previous neuroimaging and behavioral studies (Beaty et al., 2014; Benedek et al., 2012; Vartanian, 2009), our findings supported a dual process model of creativity according to which inhibitory control is required to overcome fixation effects in idea generation (Cassotti et al., 2016b). Although our results clearly demonstrated the involvement of cognitive control in creativity, one limitation of the present study might be that our findings failed to determine whether the dual-task cost depended specifically on inhibitory control or whether it resulted from a more general executive control cost.

To determine whether creative idea generation depends specifically on the ability to inhibit fixation effects, the dual-task costs under a secondary WM task were examined in a second experiment. We reasoned that if the generation of creative solutions in the egg task depended specifically on the ability to inhibit fixation effects, then creativity should not decrease under the secondary WM task load. In contrast, if creative idea generation requires broader executive function resources, then creativity should also be impaired under the secondary WM task load. Finally, if WM is detrimental to creativity as suggested by Lin and Lien (2013b), then creative performance should be higher under the secondary high-demanding WM task load. Indeed, in line with the hypothesis that creative idea generation operates automatically, Lin and Lien (2013b) have previously showed that depleting participants' WM resources using a dual-task paradigm increases the fluidity in a divergent thinking task.

Experiment 2

Method

Participants. A new sample of 79 undergraduate students (57 females, 22 males, mean age = 21.03 years, range = 18–32 years, SD = 2.64) from Paris Descartes University participated in this experiment. Each participant was randomly assigned to one of three experimental conditions: a high-demanding WM dual-task condition (n = 25), a low-demanding WM control dual-task condition (n = 25), and a single-task condition in which participants performed the creative task without a secondary task load (n = 29). The mean age did not significantly differ between the three conditions, $F(1, 76) < 1$. All participants reported normal or corrected-to-normal vision. All of the participants provided written consent and were tested in accordance with national and international norms governing the study of human research participants.

Design and procedure. Regardless of the experimental conditions, participants performed the egg task (see Experiment 1), in which they were given 5 min to propose as many original solutions as possible (Agogué et al., 2014a, 2014b, 2015; Cassotti et al., 2016b). In both dual-task conditions, they were asked to orally provide their answer as soon as it came to their mind while performing either a computerized high-demanding WM task (i.e., the WM dual-task condition) or a computerized low-demanding WM task (i.e., the control dual-task condition). In both conditions, the participants were tested using laptop computers with a screen resolution of 1,366 × 768 pixels (310 × 170 mm^2). Stimuli were presented using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA).

In both dual-task conditions, the participants were required to complete the dot memory task (De Neys, 2006a, 2006b). In the dot memory task, participants were instructed to memorize the sequence of presentation of four dots in a 4 × 4 matrix (see Figure

3). Each dot was presented during 1,000 msec. After the presentation of the fourth dot, an orange matrix was displayed for 1,000 msec before the presentation of an empty matrix. As soon as the empty matrix was displayed, participants were asked to reproduce the pattern of dot locations by selecting with the mouse the successive location of the dots on the empty matrix displayed on the screen. It is critical to note that in the WM load condition, the matrix contained complex four-dot patterns whereas in the control load condition, the patterns consisted of four dots on a horizontal or diagonal line. Each condition involved 22 experimental trials that were randomly presented. To control that each participant performed the same number of trials in each condition, the empty response matrix remained on the screen until the participant responded, within a time limit of 7,000 msec. After each trial, they received feedback on the accuracy of their responses. The duration of the feedback ranged from 1,000 to 7,000 msec depending on the response time of the participant in such a way that the cumulate duration of the response matrix and the feedback reaches 8,000 msec in total on each trial. To ensure that the participants performed the dual task, we excluded those with a performance on the WM tasks that was lower than 2 MADs from the median of the group. Thus, one participant from the control dual-task condition was excluded from the subsequent analysis.

To determine whether the high-demanding WM task requires additional WM resources compared with the low-demanding WM task, we conducted a control study on 21 participants (4 men, 17 women, mean age = 20.80 years, *SD* = 1.88 years). Participants completed both tasks and the order of presentation of the tasks was counterbalanced across participants. As expected, participants required less time to perform the low-demanding WM trials (*M* = 1,649 msec, *SD* = 337.2 msec) than the high-demanding WM trials (*M* = 1,867 msec, *SD* = 406.8 msec), $t(20) = 2{,}82$, $p = .01$, $d = 0.61$. In addition, participants were less accurate (i.e., accuracy rate) in the high-demanding WM task (*M* = 82%, *SD* = 13%) than in the low-demanding WM task (*M* = 93%, *SD* = 7%), $t(20) = 4{,}48$, $p < .001$, $d = 0.97$. Thus, we are confident that the high-demanding WM task requires additional WM resources than the low-demanding WM task.

Results

The fluidity, flexibility, and expansivity scores were submitted to one-way ANOVAs with condition as a between-subjects factor (a high-demanding WM dual-task condition, a low-demanding WM control dual-task condition, and a single-task condition). The analysis revealed no significant main effects of condition for

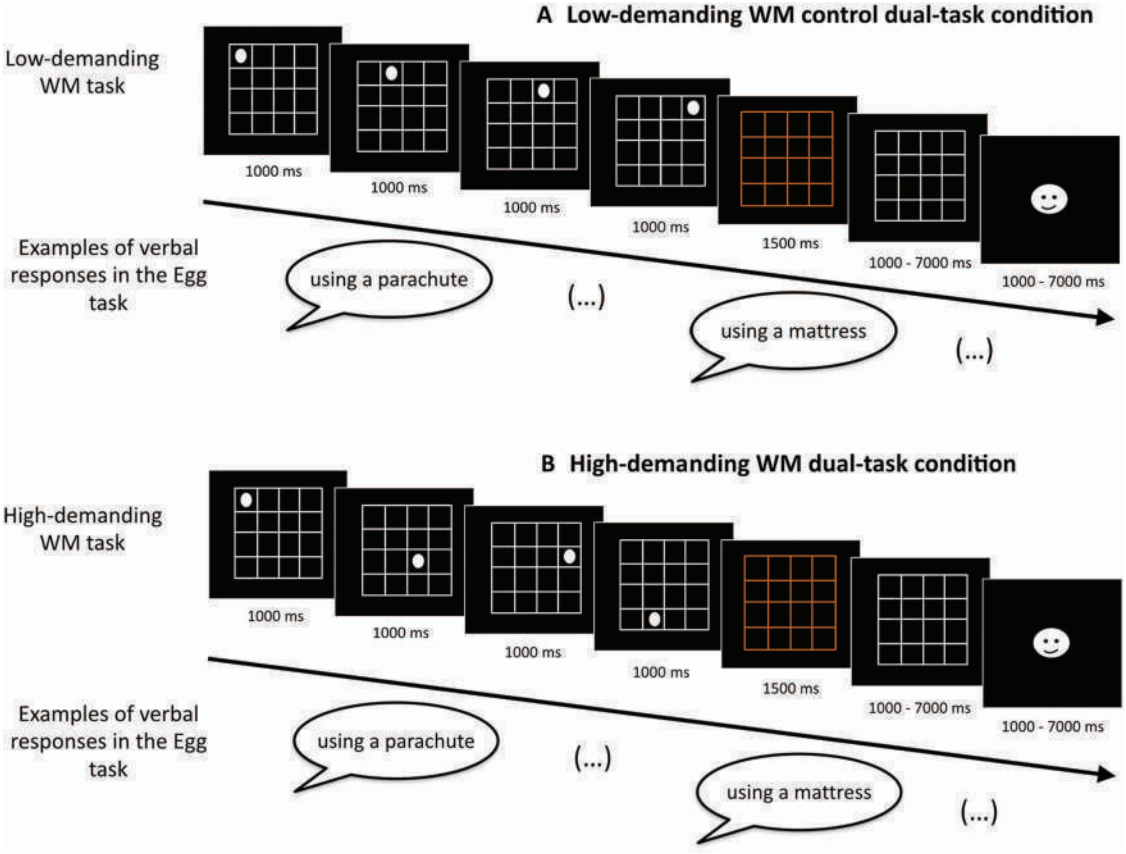

Figure 3. (A) Example of trials in the low-demanding control dual-task condition and (B) the high-demanding dual-task condition. In addition, the text bubbles are examples of verbal responses provided by the participants in the egg task that could occur at any moment during both the low-demanding control dual-task condition and the high-demanding dual-task condition. See the online article for the color version of this figure.

fluidity, $F(2, 75) < 1$ (see Figure 2B), or expansivity, $F(2, 75) < 1$. Regarding fluidity, further independent t tests confirmed the lack of significant difference between participants in the high-demanding WM dual-task condition ($M = 11.08$, $SD = 5.73$) and those in the single-task condition ($M = 10.45$, $SD = 5.36$), $t(52) = 0.42$, $p = .68$. Similar results were obtained for the expansivity measures. The analysis revealed no significant differences between participants in the WM dual-task condition (expansivity: $M = 5.24$, $SD = 4.31$) and those in the single-task condition ($M = 5$, $SD = 2.45$, $t(52) = 0.25$, $p = .81$).

General Discussion

The purpose of the present study was to determine the potential role of inhibitory control in creative idea generation. Two major findings emerged from this investigation: (a) participants' ability to provide creative ideas decreased under inhibitory control load (Experiment 1) whereas (b) WM load had no significant effect on creative ideation (Experiment 2). Taken together, these results confirm that inhibitory control is critical to overcoming fixation effects and generating original solutions in a creative task. Moreover, our results extend the findings of previous correlational studies by revealing a more causal link between the availability of inhibitory control resources and creative capabilities (Beaty et al., 2014; Benedek et al., 2012; Vartanian, 2009). In contrast with the assumption that "disinhibition" and reduced WM resources foster remote associations and stimulate creativity (Lin & Lien, 2013a, 2013b; Radel et al., 2015), the results of Experiment 1 and Experiment 2 did not find that inhibitory control or WM load had any stimulation effects. However, in agreement with the dual process model of creativity (Cassotti et al., 2016a), the ability to inhibit intuitive-heuristic thinking (System 1) leading to fixation seemed fundamental to generating creative ideas by allowing individuals to adopt other types of System 2 reasoning (e.g., analogical thinking and conceptual expansion).

An alternative interpretation of the absence of an effect of WM load on creativity might be that the WM task was too easy when compared with the interference condition of the Color Word Stroop task. However, this hypothesis seems less likely because the task used in the present study has been proven to be effective in reducing WM resources in dual-task paradigms for other domains such as reasoning and decision-making (see, e.g., Bago & De Neys, 2017; De Neys, 2006a, 2006b). In addition, even if this task only requires one to store information and does not require the manipulation of the information per se, we note that the dot matrix task seems to tax executive processes as suggested by the correlations observed between this task and the tower of Hanoi or the random number generation task, two classical executive function tasks (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). However, further studies are needed to determine whether a more executive demanding version of the dot memory task requiring, for example, one to recall dots in backward order might negatively influence creative idea generation.

Conclusion

The present study is the first to demonstrate a cost of inhibitory control load during creative idea generation using a dual-task paradigm. Our results clearly suggest that not all executive functions are involved in creative thinking and that inhibitory control is a core process of creative ideation. Accordingly, the present study provides new evidence for the current debate on the role of inhibitory control in creative idea generation.

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RESEARCH ARTICLE

How minimal executive feedback influences creative idea generation

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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 (η_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

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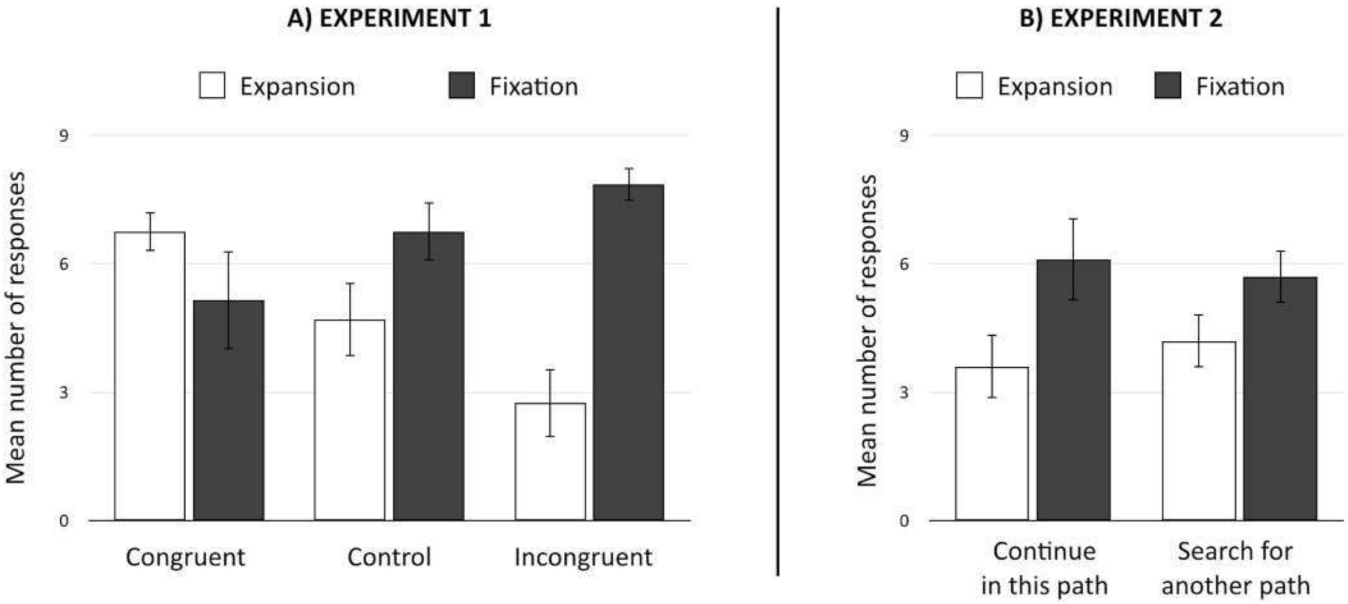

Fig 1. Mean number of solutions according to the experimental condition (A: Congruent/Control/Incongruent; B: Continue in this path/Search for another path) and the type of solution (Expansion/Fixation).

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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 (η_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)

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5

Inhibitory Control as a Core Process of Creative Problem Solving and Idea Generation from Childhood to Adulthood

Mathieu Cassotti, Marine Agogué, Anaëlle Camarda, Olivier Houdé, Grégoire Borst

Abstract

Developmental cognitive neuroscience studies tend to show that the prefrontal brain regions (known to be involved in inhibitory control) are activated during the generation of creative ideas. In the present article, we discuss how a dual-process model of creativity—much like the ones proposed to account for decision making and reasoning—could broaden our understanding of the processes involved in creative ideas generation. When generating creative ideas, children, adolescents, and adults tend to follow "the path of least resistance" and propose solutions that are built on the most common and accessible knowledge within a specific domain, leading to fixation effect. In line with recent theory of typical cognitive development, we argue that the ability to resist the spontaneous activation of design heuristics, to privilege other types of reasoning, might be critical to generate creative ideas at all ages. In the present review, we demonstrate that inhibitory control at all ages can actually support creativity. Indeed, the ability to think of something truly new and original requires first inhibiting spontaneous solutions that come to mind quickly and unconsciously and then exploring new ideas using a generative type of reasoning. © 2016 Wiley Periodicals, Inc.

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The ability to inhibit prepotent associations or previous and inappropriate ideas seems to be a critical process to generate new ideas and creative solutions to problems (Dietrich & Kanso, 2010). Although considerable efforts in the field of developmental psychology and neuroscience have been devoted to identifying the role of inhibitory control in reasoning and decision making (Crone & Dahl, 2012; Houdé & Borst, 2014, 2015), there are to date few studies that have examined whether this executive function may facilitate creative ideation at all ages (Kleibeuker, Koolschijn, Jolles, De Dreu, & Crone, 2013a). This relative lack of interest is partly because of how these two fields define inhibition. Indeed, many studies in the field of creativity considered inhibition as a social process hindering creativity (Kohn & Smith, 2011). According to this view, social pressure, evaluation, and conformity would lead individuals to inhibit their creative potential (Amabile, Goldfarb, & Brackfleld, 1990). Even if social inhibition is undoubtedly a fundamental aspect of creative thinking, this concept differs from the process of inhibition at the core of recent theories of typical cognitive development (Diamond & Lee, 2011). In these models, inhibition, and more specifically inhibitory control, is viewed as a basic process enabling the suppression of prepotent but irrelevant response tendencies and previously acquired knowledge (Houdé & Borst, 2014, 2015). In this article, we discuss how developmental models that emphasize the role of inhibitory control in overcoming reasoning and decision-making biases could broaden our understanding of the processes involved in creative problem solving and idea generation. Specifically, we examine whether the ability to think of something truly new (i.e., original, unexpected) and appropriate (i.e., useful, adaptive concerning task constraints, see Sternberg & Lubart, 1996) requires first inhibiting easy solutions that spontaneously come to mind and then generating creative ideas.

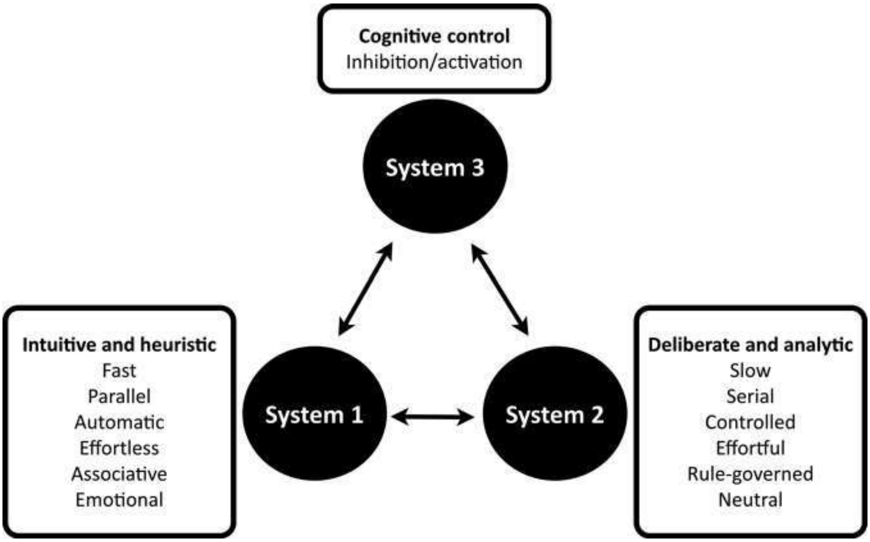
Dual Process Theory and Reasoning-Biases Inhibition

Consider the following example:

> In a lake, there is a patch of lily pads. Every day, the patch doubles in size.
>
> If it takes 48 days for the patch to cover the entire lake, how long would it take for the patch to cover half of the lake? _____ days

When trying to answer this problem, an intuitive response spontaneously comes to mind: 24 days (Frederick, 2005). It is true that most of the time to get half a set, the most basic solution is to divide it by two. However, this response that immediately jumps to mind is false! Indeed, we tend to ignore a fundamental and explicitly mentioned part of the problem, which is that every day, the patch doubles in size. Thus, the correct response is "47 days" because the patch of lily pads will cover half of the lake surface

Figure 5.1. Schematic representation of the dual process models (see Houdé & Borst, 2014)



on the 47th day, and doubling it overnight will cover the full surface the 48th day. To explain such reasoning biases, authors have postulated the existence of two distinct system of thinking (De Neys, Rossi, & Houdé, 2013; Houdé, 1997; Kahneman, 2011). Dual system theories generally oppose an intuitive-heuristic system (named System 1) to a deliberate-analytic system (named System 2). System 1 operations are typically effortless, rapid, global, or holistic, and often emotionally charged. System 2, in contrast, is slow, controlled, serial, effortful, and involves cognitively costly strategies (see Figure 5.1). Consequently, these dual theories predict qualitatively different judgments and decisions depending on which system is running.

According to this theoretical framework, cognitive biases evidenced in children, adolescents, and adults are not due to a lack of logical skills *per se*, but result from a specific failure to inhibit intuitive responses generated automatically by System 1. Thus, to solve reasoning problems such as "the patch of lily pads" problem, one must first inhibit (System 3) the misleading heuristic belonging to System 1, and then activate the logical algorithm of System 2.

From a developmental perspective, studies converged in showing that an increasing number of heuristics are acquired over the course of development that are used with increasing frequency (De Neys & Vanderputte, 2011; Houdé & Borst, 2014; Reyna, Wilhelms, McCormick, & Weldon, 2015). With the respective development of the intuitive-heuristic System 1 and the deliberative-analytic System 2, the experiences of conflict and inhibitory control demand may change with age. In addition, several lines of evidence suggest that the ability to inhibit the misleading intuitive strategies improves from childhood to late adolescence (De Neys & Van Gelder, 2009; Houdé & Borst, 2014, 2015). Unlike other traditional models of cognitive development such as the Piagetian model, these dual-process models, by focusing not only on the development of the two systems but also on the development of inhibitory control abilities, can account for nonlinear patterns of development observed in reasoning and decision making (Houdé & Borst, 2014, 2015).

Fixation and Inhibition in Creative Problem Solving

Much like researchers in the field of reasoning seeking to understand what causes one to fail to reason logically, researchers in the field of creativity seek to determine the factors leading one to fail to provide original ideas or problem solutions. For instance, numerous studies have reported that creative problem-solving capabilities can be blocked by mental fixation (Storm & Angello, 2010). These studies stress how previous knowledge or ideas can constrain the generation of alternative solutions during creative problem solving. One of the most striking examples of this creativity failure is the so-called functional fixedness phenomenon, initially described by Duncker (1945). For instance, in the "candle problem" (Adamson, 1952; German & Barrett, 2005), participants are presented with a tabletop containing a book of matches, a box of tacks, and a candle. They are asked to find a way to fix and light the candle on the wall in such a way that it will burn without dripping wax onto the table below.

This problem is difficult to solve because people are fixed on the traditional function of the box as a container. Indeed, the optimal solution requires emptying the box of tacks to use it in an unfamiliar way such as a platform. Frequently, adults fail to easily find this solution when the box is presented as being full of tacks because they remain focused on the typical function of the box.

Within the context of dual-process models, functional fixedness may arise from an intuitively-generated mental representation of the classical use of the object belonging to System 1. Therefore, inhibitory control may allow the suppression of this first intuitive response in order to consider alternative uses of the objects. Although no study has demonstrated a direct relationship between inhibitory control and creative performance in the candle problem, there is increasing evidence that the ability to overcome fixation in various problem-solving situations require inhibitory control (Dietrich & Kanso, 2010; Storm & Angello, 2010; Storm & Patel, 2014). Indeed, studies in adults clearly demonstrated that higher level of inhibitory control is associated with greater success on creative problems solving tasks involving mental fixation (Storm & Angello, 2010). Additional empirical evidences in favor of the hypothesis that inhibitory control is a core component of creative problem solving came from a developmental neuroimaging study in adolescent and adults (Kleibeuker et al., 2013b). Greater activation of the inferior frontal gyrus and the dorsolateral prefrontal cortex, two brain regions classically associated with executive functions and inhibitory control in particular, were observed when participants provided optimal solutions to the problems. In addition, these two brain structures were more activated in adolescents than in adults, suggesting that the maturation of the prefrontal cortex regions sustaining inhibitory-control ability is still developing during adolescence in agreement with the protracted development of these prefrontal regions until early adulthood (Giedd et al., 2009).

Developmental studies of functional fixedness have reported, surprisingly, that 5- and 6-year-old children seem immune to this cognitive bias as opposed to older children and adults (Defeyter & German, 2003; German & Barrett, 2005; German & Defeyter, 2000). Indeed, using a child-friendly adaptation of the candle problem, German and Defeyter (2000) clearly demonstrated that young children are not fixed on the typical function of the object, allowing them to solve the problem more easily than older children. This finding makes sense in light of dual-process models of cognitive development according to which heuristics belonging to System 1 progressively emerge during the course of childhood (Houdé & Borst, 2014). This result is also consistent with results in decision-making studies showing that young children are less susceptible to various cognitive biases (Reyna, Wilhelms, McCormick, & Weldon, 2015). Whereas overcoming functional fixedness in older children and adults requires inhibitory control, younger children might not need inhibitory control to generate alternative function of objects because the classical functions of the object might not be as strong as in adolescents and adults. In other words, children might not need inhibitory control in these contexts to be creative simply because, unlike adolescents and adults, they experience a lower functional fixedness (or at least a different type of fixation) in creative problem solving.

Fixation and Inhibition in Creative Ideas Generation

Although reasoning and creative problem-solving studies suggest that inhibitory control is involved in overcoming cognitive biases and mental fixation, one could wonder whether this process is also fundamental in circumstances where individuals cannot simply choose between existing strategies but must propose a variety of new strategies (DeHaan, 2011). Just as in other contexts, it seems that individuals face numerous cognitive biases when asked to generate creative ideas (Finke, Ward, & Smith, 1992; Ward, Patterson, & Sifonis, 2004). Indeed, people tend to follow "the path of least resistance" and propose solutions that are built on the most common and accessible knowledge within a specific domain (Agogué et al., 2014; Smith, Ward, & Finke, 1995). For example, when individuals must imagine and draw an animal that lives on another planet very different from

Earth, a number of typical examples of animals living on Earth spontaneously jump to mind (Abraham & Windmann, 2007). These intuitive and spontaneous representations of what classically constitute animals on Earth (bilateral symmetry of the shape, presence of common appendage or sense organs) impede the creative process, leading to fixation effect in both children and adults (Cacciari, Levorato, & Cicogna, 1997). According to the dual-process view and in line with the "path of least resistance" model (Ward et al., 2004), the difficulty of generating creative ideas might result from a specific failure to inhibit intuitive responses leading to fixation effect generated automatically by System 1. Thus, to provide original ideas in a problem such as "the alien drawing task," one must first inhibit the intuitive representations of what classically constitute animals on Earth (representations belonging to System 1) and then activate conceptual expansion reasoning (in System 2).

Interestingly, the results of a recent study suggest that the nature of fixation effect during the generation of creative ideas may develop with age, education, and expertise (Agogué, Poirel, Pineau, Houdé, & Cassotti, 2014). Using a creative idea generation task that involves designing a method to drop a hen's egg from a height of 10 meters (32 feet) to ensure that it does not break (called "the egg task"), the authors found that the fixation effect of children diverges qualitatively from that of adults. Indeed, most of the responses proposed by the adults were based on spontaneously activated knowledge and consisted of using an inert device to dampen the shock, protect the egg, or slow the fall (e.g., to slow the fall with a parachute). On the contrary, more original solutions that consisted of using a living device or of modifying the natural properties of the egg (e.g., training a bird to catch the egg during the fall or freezing the egg before dropping it) were less often provided by the participants. Although 10-year-old children were also fixed on solutions that consisted of protecting the egg or dampening the shock, they did not spontaneously propose to slow the fall using, for example, a parachute. In line with dual-process models, these results suggest that the design heuristics belonging to System 1 used by participants to explore the potential solutions to the task and leading to fixation differed between children and adults, although children knew what parachutes were and how parachutes worked. Moreover, a recent study on industrial designer with the same egg task provided indirect evidence that inhibitory control might be involved in the ability to overcome fixation effect during creative ideas generation (Agogué, Le Masson, Dalmasso, Houdé, & Cassotti, 2015). The authors found that industrial designers outperformed engineers with regard to fluency and originality, and gave more solutions outside of the fixation effect in the egg task. It was argued that industrial designers outperformed engineers because they were more efficient at inhibiting fixation effect. This assumption is in line with results of a previous study showing that industrial designers exhibited higher scores of creativity assessed with the Torrance Tests of Creative Thinking and showed higher inhibitory control skills as indicated by the absence of a Stroop interference effect (i.e., a classical inhibitory control task) compared to a control group. In addition, the creative abilities of industrial designers were positively associated with their performance on the Stroop task (Edl, Benedek, Papousek, Weiss, & Fink, 2014).

Additional evidence for the role of inhibitory control and flexible cognitive control in creative ideas generation has been provided by a series of studies showing positive correlations between inhibition measures and divergent thinking performance in adults (Beaty, Silvia, Nusbaum, Jauk, & Benedek, 2014; Benedek, Franz, Heene, & Neubauer, 2012; Vartanian, 2009; Zabelina & Robinson, 2010). Moreover, neuroimaging studies have consistently reported a relationship between the ability to generate highly creative responses and activations in specific prefrontal brain regions known to be implicated in executive functions (Benedek et al., 2014; Dietrich & Kanso, 2010). More specifically, verbal and visuospatial creativity elicited activations in the anterior cingulate cortex, the inferior frontal gyri, and the middle frontal gyri, suggesting that conflict monitoring, inhibitory control, and working memory might be important for creativity (Boccia, Piccardi, Palermo, Nori, & Palmiero, 2015). Critically, a recent neuroimaging study demonstrated that brain activation in the inferior frontal gyrus—a brain region known to be implicated in inhibitory control (Houdé, Rossi, Lubin, & Joliot, 2010)—is positively related to originality and appropriateness aspects of divergent thinking (Benedek et al., 2014). Studies showing that more creative adults have better inhibitory control efficiency and recruit to a greater extent brain regions involved in inhibitory control than less creative adults are in agreement with the prediction of our dual-process model of creativity that creative idea generation requires the inhibition of dominant and common ideas belonging to System 1 to explore new concepts using a generative type of reasoning (conceptual expansion or analogical reasoning).

Despite these recent findings on adults, there are few developmental studies on the relationship between inhibitory control and creative idea generation in children and adolescents. To the best of our knowledge, only one developmental neuroimaging study has directly tested the involvement of inhibitory control brain regions in divergent thinking in a developmental perspective (Kleibeuker et al., 2013a). In this elegant study, the authors investigated the neural correlates of multiple creative ideas generation in both adolescents and adults. Using an alternative uses task in which participants were requested to generate alternative uses for conventional everyday objects such as a brick, they reported that brain activations in the left lateral prefrontal cortex regions supporting inhibitory control process were less activated in adolescent than in adults. Consistent with dual-process models postulating that inhibitory control is still developing during adolescent, these findings suggest that adolescent may be less effective to execute inhibitory control on intuitively generated solutions based on the typical function of the objects in the alternative uses task (i.e., fixation effect belonging to the intuitive System 1) compared to adults.

Limitations

In the present review, we have discussed how a dual-process model of creativity—much like the ones proposed for reasoning and decision making—may lead to significant progress in the understanding of the processes involved in creative cognition. Nevertheless, a few limitations of the present study should be acknowledged. First of all, because creativity is a complex phenomenon, different factors such as personality traits, emotional context, and social influences are known to highly contribute to creative performance. Although our model provides a basis for studying the development of creativity, and more specifically here, creative behaviors that include creative problem solving and creative ideas generation, further researches are necessary to determine how these critical factors modulate the activation of each system and the interactions between them.

The role of inhibitory control in creative ideas generation has been evidenced with verbal divergent thinking studies but few studies have investigated whether inhibitory control is also required to be creative in other domains such as in visuospatial or artistic creativity. The results of a meta-analysis of neuroimaging studies of creativity in three different domains including musical, verbal, and visuospatial (Boccia et al., 2015) suggest that verbal and visuospatial creativity, but not musical creativity, rely on the activation of a network of executive brain regions including inhibitory control ones. Thus, inhibitory control might be required to be creative only in the verbal and visuospatial domains.

Finally, although neuroimaging and behavioral studies converge in showing that better inhibitory control leads to higher creativity, some studies have reported that poorer inhibitory ability can facilitate creative performance (Radel, Davranche, Fournier, & Dietrich, 2015). For example, using noninvasive brain stimulation, Mayseless and Shamay-Tsoory (2015) reported that decreasing the activity in the left frontal parts of the brain and increasing activity in the right frontal parts of the brain—a brain modulation supposed to reduce cognitive control—have a positive effect on creative ideas production. In sharp contrast with this finding, another noninvasive brain stimulation study reported that a hyperactivation of the prefrontal cortex was beneficial for creative production, suggesting that better cognitive control led to better creative ideas generation (Colombo, Bartesaghi, Simonelli, & Antonietti, 2015). In a similar vein, numerous studies on clinical disorders associated with inhibitory control deficits suggest that impaired cognitive control might facilitate original associations and stimulate creative ideas generation (see de Souza et al., 2014). We note, however, that these patients rarely exhibited specific deficits in inhibitory control. Thus, to account for the discrepancies in the literature regarding the role of creativity, future researches should explore the respective contribution of latent inhibition, social inhibition, and cognitive inhibition to creativity.

Conclusion

Taken together, the behavioral and neuroimaging data reviewed in this article converge in showing that the development of creative problem solving and idea generation relies not only on the ability to make intuitive associations but also on the ability to suppress (inhibit) previously acquired knowledge or prepotent irrelevant classical solutions.

In contrast to the assumption that reduced inhibitory control may foster remote associations and stimulate creativity (Radel et al., 2015), we have reported numerous evidence in the literature that the ability to resist (inhibit) intuitive-heuristic reasoning leading to fixation is critical to generate creative solutions to problems at all ages by allowing one to adopt other types of reasoning (e.g., analogical thinking and conceptual expansion) belonging to System 2.

Although an increasing number of studies in adults focus on the role of inhibitory control in creative thinking (Beaty et al., 2014; Benedek et al., 2012, 2014; Dietrich & Kanso, 2010; Storm & Angello, 2010), there are still many challenges to be addressed to fully understand the processes that enable to break conventional or obvious patterns of thinking in a developmental perspective of creative ideas generation. Indeed, more research is required to clarify the relationship between creativity and the developmental trajectories of fixation effects (System 1), generative-type of reasoning (System 2), and inhibitory control (System 3). This new line of developmental research should also clarify the interactions between these systems to determine whether System 1 and System 2 are activated serially or in parallel (De Neys et al., 2013). Finally, given that previous developmental studies demonstrated that inhibitory control can be improved (Diamond & Lee, 2011), studies should investigate whether interventions based on training inhibitory control can help children, adolescents, and adults overcome fixation effects during creative problem solving and idea generation.

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Fixation effect in creative ideas generation: Opposite impacts of example in children and adults

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ABSTRACT

Recent research with adults has shown that exposure to examples does not systematically constrain creativity and can, on the contrary, have a stimulating effect. In the present study, we examined the potential influence of examples on the generation of creative ideas in school-age children and adults. We utilized the egg task, in which participants design a method to drop a hen's egg from a height of 10 m to ensure that it does not break. First, we conducted a pilot study to confirm that the nature of the fixation effect in the egg task differs between children and adults, and we then explored the potential influence of examples on creative idea generation in a second study. The results revealed that exposure to the same example during a creative task has two opposite effects: adults were constrained in their ability to propose solutions, whereas this ability was enhanced in children. We explain this differing effect by noting that the same example can be within fixation for adults and outside fixation for children. The positive effect of examples allowed children to exhibit performance that was comparable to that of adults with regard to fluency and flexibility.

1. Introduction

The ability to generate new ideas and creative solutions to problems is crucial for adapting to a changing and open-ended environment. This need is particularly apparent during circumstances in which individuals cannot simply choose between existing strategies but must create new strategies (DeHaan, 2011). From this perspective, creativity is a fundamental process that influences many areas of daily life, such as education and scientific reasoning. Cognitive psychology scholars who study creativity have identified a number of obstacles that most people are likely to encounter during idea generation (Abraham & Windmann, 2007; Smith, Ward, & Finke, 1995; Ward, Patterson, & Sifonis, 2004). Indeed, people tend to follow "the path of least resistance" and propose solutions that are built on the most common and accessible knowledge within a specific domain. For instance, when individuals must imagine and design a new original chair, a number of typical examples of chairs spontaneously come to mind. These spontaneous representations of what classically constitutes a chair may block

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the creative process, leading to a phenomenon called the “fixation effect” (Smith et al., 1995). Studies converge in showing that the fixation effect is reinforced when adults are exposed to examples of solutions before being asked to generate new ideas. For example, in a series of experiments, Smith, Ward, and Schumacher (1993) asked participants to imagine and draw new toys for a toy company. Participants were specifically told that their toys had to differ substantially from currently or previously existing toys. Prior to drawing the toys, participants were exposed to examples that had fundamental elements in common (e.g., the presence of a ball). Independent experimenters coded whether the subjects’ drawings contained any of the pre-cited elements. The results showed that participants tended to incorporate these elements into their own drawings, despite the explicit warning to avoid replicating features from the examples. These results are consistent with those of other studies (Jansson & Smith, 1991; Landau, Thomas, Thelen, & Chang, 2002; Landau & Leynes, 2004).

However, Agogué, Kazakçi, et al. (2014) recently demonstrated that exposure to examples does not systematically lead to constraining creativity and can, on the contrary, have a stimulating effect (see also Dugosh & Paulus, 2005; Fink et al., 2010 Indeed, utilizing a creative idea generation task that involves designing a method to drop a hen’s egg from a height of 10 m to ensure that it does not break (called “the egg task”), the authors clearly showed that both the constraining and the stimulating effects of examples depend on the nature of the examples that are proposed prior to solving the task. The results indicated that the introduction of examples consisting of solutions generated using the most accessible knowledge constrained creativity, whereas examples consisting of less spontaneously accessible solutions reduced the fixation effect and stimulated originality. Thus, examples outside the fixation effect led participants to propose more original solutions, whereas examples within the fixation effect reduced both the number and the originality of the proposed solutions. Studies in the domain of analogical problem solving have reached to very similar conclusions (Bonnardel, 2000; Casakin & Goldschmidt, 1999). For example, Bonnardel and Marmeche (2004) reported that intradomain analogies decreased the production of new ideas in expert designers whereas interdomain analogies have the opposite effect, enhancing the evocation processes.

From a developmental perspective, studies examining creative thinking have obtained inconsistent results. For example, Jaquish and Ripple (1980) reported that fluency (i.e., the number of proposed solutions) and flexibility (i.e., the number of categories of proposed solutions) but not originality increase between children and adolescents, whereas Kleibeuker, De Dreu, & Crone (2013) utilized a creative task in which participants had to find alternative uses for conventional objects, demonstrating that originality rather than fluency or flexibility continues to develop during late adolescence. During an examination of divergent thinking skills in children and adults, Wu, Cheng, Ip & McBride-Chang (2005) observed that creativity regarding real-world problems increased between 10- to 12-year-old children and university students but decreased in the same age range on a figural task, suggesting that developmental patterns may depend on the types of tasks used to assess creativity.

Although numerous studies have examined the developmental trajectories for the ability to generate creative ideas across childhood and adolescence (Claxton, Pannels & Rhoads, 2005; Jaquish & Ripple, 1980; Kleibeuker, De Dreu, et al., 2013; Lau & Cheung, 2010; Wu et al., 2005), little is known about the potential influence of examples on children’s creativity. Previous research suggests that the influence of the fixation effect during the generation of creative ideas varies with age and expertise (Agogué, Poirel, Pineau, Houdé & Cassotti, 2014; Defeyter & German, 2003; German & Barrett, 2005). Specifically, a recent investigation conducted a qualitative analysis of responses to explore how age and education influence the fixation effect during the egg task (Agogué, Poirel, et al., 2014). Although most of the solutions proposed by adults consisted of slowing the fall, protecting the egg or dampening the shock, 10-year-old children did not spontaneously propose to slow the fall using, for example, a parachute. Preliminary results indicated that the accessible knowledge and design heuristics that participants used to explore the potential solutions to the task leading to the fixation phenomena differed between children and adults, despite children having the required knowledge base (e.g., they knew what parachutes were and how parachutes worked).

Based on these previous studies (Agogué, Poirel, et al., 2014), the following two hypotheses can be formulated regarding the influence of examples on creativity in children and adults: (1) exposure to examples of solutions based on the most accessible knowledge (within the fixation effect) should block the ability of adults to generate original ideas, and (2) if children do not show the same fixation effect as adults, then examples within the fixation effect for adults may serve as examples outside the fixation effect for children, which may decrease the ability of adults to generate original ideas and enhance children’s ability to propose solutions to creative tasks.

Thus, in the present study, we examined the potential effect of examples on the generation of creative ideas in school-age children and adults. To determine whether the introduction of examples of solutions influences the capacity to generate creative ideas, we utilized the egg task, in which participants must design a strategy to drop a hen’s egg from a height of 10 m to avoid breaking it. First, we conducted a pilot study to confirm that the nature of the fixation effect during the egg task differs between children and adults, consistent with Agogué, Poirel, et al. (2014) study. We then explored the potential influence of examples on the generation of creative ideas in a second study. To do so, participants were randomly assigned to one of the following two experimental conditions: a control condition without examples and a test condition in which a typical example of a solution was provided in the design brief.

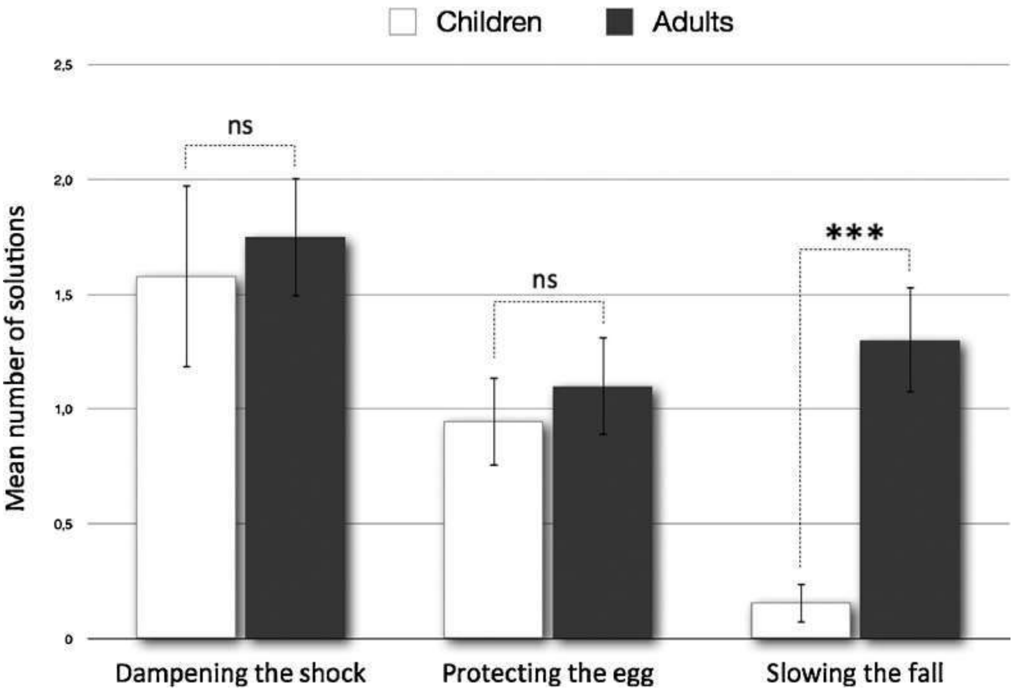

Fig. 1. Mean number of solutions provided during the egg task according to the three meta-categories of fixation. $^{***}p < 0.005$.

2. Study 1

2.1. Method

2.1.1. Participants

Two age groups participated in the pilot study: 19 children from 9 to 11 years of age (7 girls and 12 boys, mean age = 9.6 years, SD = 0.6) and 20 adults from 18 to 22 years of age (11 women and 9 men, mean age = 19 years, SD = 1.3). The gender distributions did not significantly differ across age groups (χ_2 (1) = 1.3, $p = 0.26$). Parental written consent was obtained for all children, who were tested in accordance with national and international norms governing the use of human research participants. All children attended the same elementary school, and the adults were university students.

2.1.2. Design and procedure

Each participant was given ten minutes to solve the following paper and pencil problem:

The experiment was conducted at the beginning of a lecture, with all participants in the same classroom. The task was administered silently and individually, and the participants were instructed to write down their solutions using short sentences.

Two trained raters assigned each solution given by the participants to one of 54 solution categories (e.g., "using a pool of water on the floor to dampen the shock") and assigned these categories to one of the 10 meta-categories identified by Agogué, Poirel, et al. (2014). Inter-rater agreement was excellent (percent agreement = 97%). Based on a previous study (Agogué, Poirel, et al., 2014), three meta-categories (i.e., dampening the shock, protecting the egg, and slowing the fall) met the qualifications for the fixation effect, whereas the seven others did not (e.g., using a living device such as training an eagle to catch the egg and modifying the natural properties of the egg).

3. Results and discussion

The number of solutions for each of the three meta-categories (see Agogué, Poirel, et al., 2014), which were "slowing the fall," "protecting the egg" and "dampening the shock," were submitted to independent *t*-tests, which revealed the predicted effect of age on the nature of the fixation (see Fig. 1). Specifically, children and adults proposed similar numbers of responses related to protecting the egg (Children: 0.95 ± 0.85, Adults: 1.1 ± 0.97, $t(37) = 0.52$, $p = 0.60$, $d = 0.18$) and dampening the shock (Children: 1.58 ± 1.74, Adults: 1.75 ± 1.16, $t(37) = 0.36$, $p = 0.71$, $d = 0.11$). By contrast, children proposed fewer responses related to slowing the fall than adults did (Children: 0.16 ± 0.37, Adults: 1.3 ± 1.03, $t(37) = 4.55$, $p < 0.0005$, $d = 1.46$). These results are consistent with a previous study showing that the nature of the fixation effect during the egg task changes with age (Agogué, Poirel, et al., 2014).

Therefore, we can hypothesize that examples of solutions from the “slowing the fall” meta-category, such as “using a parachute,” should increase the ability of children to propose a set of creative solutions to the egg task and should decrease the ability of adults to generate original ideas.

4. Study 2

4.1. Method

4.1.1. Participants

This study included 60 participants. The sample was divided into two age groups: 32 children from 9 to 10 years of age (18 girls and 14 boys, mean age = 10.1 years, SD = 0.5) and 32 adults from 18 to 22 years of age (19 women and 13 men, mean age = 18.68 years, SD = 0.78). The gender distributions did not significantly differ across age groups (χ_2 (1) = 0.15, $p = 0.69$). Each participant was randomly assigned to one of the two following experimental conditions: a control group with no example ($N_{\text{children}} = 18$, mean age: 10.05, SD = 0.23 and $N_{\text{Adults}} = 17$, mean age: 18.55, SD = 0.87) and a group exposed to a very classic example ($N_{\text{Children}} = 14$, mean age: 10.14, SD = 0.66 and $N_{\text{Adults}} = 15$, mean age: 18.8, SD = 0.67). All participants were naive regarding the experimental aims, and none had experience with this specific task. Age did not significantly differ across experimental conditions (for children: $t(30) = 0.52$, $p = 0.60$; for adults: $t(30) = 0.76$, $p = 0.45$). Parental written consent was provided for all children, who were tested in accordance with national and international norms governing the use of human research participants. All children attended the same elementary school, and the adults were university students.

4.1.2. Materials and procedure

The participants were randomly assigned to one of two experimental conditions (a control condition without an example or a test condition with an example) and were given ten minutes to solve the egg task (see Section 2). The problems were identical across conditions, except that the group with an example read the following: “One possible solution is to slow the fall with a parachute”. We chose this example because it is a solution that is within the fixation effect for adults and outside the fixation effect for children (see Section 2 and Agogué, Poirel, et al., 2014; in press). The task was administered silently and individually, and participants had to write down their solutions using short sentences. Instructions for the task were provided on a sheet of paper and the experiment occurred at the beginning of a course. More specifically, participants were given ten minutes to generate as many original solutions as they could to one of the following problems (Agogué, Le Masson, Dalmasso, Houdé, & Cassotti, 2015):

Control group: without example

> “*You are a designer, and you are asked to propose as many original solutions as possible to the following problem: ensure that a hen’s egg dropped from a height of 10 m does not break*”.

Group with example: exposed to an example

> “*You are a designer, and you are asked to propose as many original solutions as possible to the following problem: ensure that a hen’s egg dropped from a height of 10 m does not break. One possible solution is to slow the fall with a parachute*”.

5. Results

To measure the effect of the example on the creativity of children and adults, we examined the three criteria proposed by Guilford (1950) to assess creativity: fluidity (the capacity to generate many solutions as measured by the number of solutions), flexibility (the capacity to generate many categories of solutions), originality (the normalized statistical infrequency of a particular solution) and feasibility.

5.1. Fluidity

To measure fluidity, we counted the number of solutions provided by the participants. When a participant proposed a solution that was a combination of different proposals, we counted each proposal as one solution.

To examine whether the number of solutions proposed (i.e., fluency) varied according to participants’ age and the experimental conditions, we conducted an analysis of variance (ANOVA) with age (children vs. adults) and the experimental condition (control vs. with example) as between-subjects factors. This analysis revealed a main effect of age ($F(1, 60) = 3.93$, $p = 0.05$, $\eta_p{}^2 = 0.06$) but no main effect of experimental conditions ($F(1, 60) < 1$). There was a significant age × experimental condition interaction ($F(1,60) = 5.05$, $p < 0.05$, $\eta_p{}^2 = 0.08$). Planned comparisons revealed that the children in the control group proposed fewer solutions than the adults in the control group (Children: 2.89 ± 1.45, Adults: 4.94 ± 1.47, $t(60) = 3.14$, $p < 0.05$, $d = 1.41$). However, the increase in the number of solutions generated by children exposed to an example and the reverse effect observed in the group of adults who received an example led children to exhibit performance that was comparable to that of adults (Children: 3.93 ± 2.43, Adults: 3.80 ± 2.34, $t(60) = 0.17$, $p > 0.20$, $d = 0.05$).

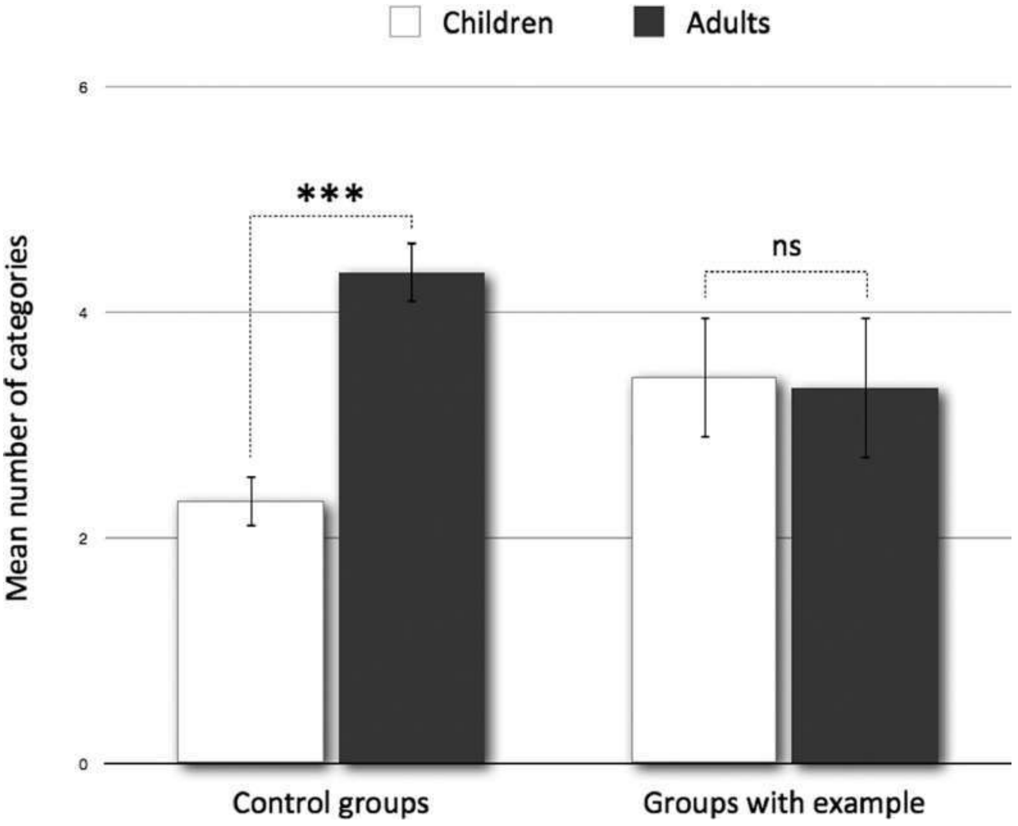

Fig. 2. Mean number of categories of proposed solutions during the egg task according to age group and experimental condition. ***$p < 0.005$.

5.2. *Flexibility*

With regard to the flexibility measure, a trained rater assigned each solution to one of 54 solution categories (e.g., “using a pool of water on the floor to dampen the shock”). Subsequently, the number of applied solution categories was counted for each participant individually. A second ANOVA on the number of categories explored (i.e., flexibility) revealed a main effect of age ($F(1, 60) = 5.09$, $p < 0.05$, $\eta_p{}^2 = 0.08$) but no main effect of experimental conditions ($F(1,60) < 1$). There was a significant age × experimental condition interaction ($F(1,60) = 6.16$, $p < 0.05$, $\eta_p{}^2 = 0.09$). Critically, the children in the control group proposed fewer categories than the adults in the control group (see Fig. 2) (Children: 2.33 ± 0.97, Adults: 4.35 ± 1.11, $t(60) = 3.52$, $p < 0.005$, $d = 1.93$). Nevertheless, the increase in the number of categories generated by children exposed to an example and the opposite effect observed in the group of adults who received an example led children to reach adult-like levels of flexibility (Children: 3.43 ± 2.03, Adults: 3.33 ± 2.44, $t(60) = 0.14$, $p > 0.20$, $d = 0.04$).

5.3. *Originality*

We also computed an objective measurement of the originality of the solutions by considering the frequency of the responses provided by all participants for each age group separately. For this score, the originality of a solution was defined as the normalized statistical infrequency of that particular solution.

The analysis revealed that the solutions proposed by the group of adults who were exposed to the example were less original than those provided by the control group (Adults with example: 0.47 ± 0.31, Control group of adults: 0.62 ± 0.1, $t(30) = 1.94$, $p < 0.05$, $d = 0.65$). By contrast, our data indicated that the group of children who were exposed to the example tended to propose more original solutions than did those in the control group without an example (Children with example: 0.42 ± 0.26, Control group of children: 0.56 ± 0.23, $t(30) = 1.6$, $p = 0.06$, $d = 0.59$).

To examine whether the number of solutions in each of the three meta-categories, which were “slowing the fall”, “protecting the egg” and “dampening the shock”, varied according to age and experimental condition, we conducted an ANOVA with age (children vs. adults) and the experimental condition (control vs. with example) as between-subjects factors and with the three meta-categories as a within-subjects factor. This analysis revealed a significant three-way interaction ($F(1,60) = 4.64$, $p < 0.05$, $\eta_p{}^2 = 0.07$). Planned comparisons revealed that the children and adults in the control groups proposed a similar number of responses related to protecting the egg (Adults: 1.24 ± 1.09, Children: 1.11 ± 1.36, $t(60) = 0.34$, $p > 0.20$, $d = 0.11$) and dampening the shock (Adults: 1.65 ± 1.17, Children: 1.0 ± 1.14, $t(60) = 1.72$, $p = 0.09$, $d = 0.50$). However, children proposed fewer responses related to slowing the fall than adults (Adults: 1.0 ± 1.0, Children: 0.22 ± 0.55, $t(60) = 2.05$, $p < 0.05$,

$d = 0.97$). Critically, our results indicate that the children who were exposed to the example proposed more solutions related to slowing the fall than did the control group of children (Children with example: 1.29 ± 1.54, Control group of children: 0.22 ± 0.55, $t(60) = 2.73$, $p < 0.01$, $d = 0.93$).

5.4. Feasibility

We applied an external rating procedure to assess feasibility. More specifically, two independent raters were instructed to evaluate each idea on a five-point rating scale ranging from 1 (“not feasible at all”) to 5 (“highly feasible”). The raters displayed satisfactory intraclass correlation (ICC = 0.90).

With regard to feasibility, the ANOVA revealed no main effect of age, $F(1, 60) < 1$, $\eta^2 = 0.05$, or the experimental conditions, $F(1, 60) < 1$, $\eta^2 = 0.08$. Critically, there was a significant interaction between age and experimental conditions, $F(1, 60) = 4$, $p = 0.05$, $\eta^2 = 0.50$, showing that solutions provided by the children after being exposed to an example are less feasible, $M = 4.25 \pm 1.28$, than those given by the control group, $M = 4.74 \pm 0.57$, whereas feasibility of the solutions given by adults were higher in the group exposed to example, $M = 4.67 \pm 0.41$, than in the control group, $M = 4.39 \pm 0.55$.

5.5. General discussion

The objectives of the present investigation were (1) to replicate the results of Agogué, Poirel, et al. (2014) showing that the nature of the fixation effect in the egg task differs in children and adults (Section 2) and (2) to explore how external clues, such as an example of a solution, affect the abilities of children and adults to generate creative ideas (Section 4). Two major findings emerged from these studies: (1) children do not show the same fixation effect as adults (Section 2) and (2) the example of solutions “using a parachute” (within the fixation effect for adults and outside the fixation effect for children) increase the ability of children to propose a set of creative solutions to the egg task and decrease the ability of adults to generate original ideas (Section 4).

Our results confirmed that the vast majority of the solutions proposed by adults belonged to one of three meta-categories: “slowing the fall”, “protecting the egg” and “dampening the shock”. These meta-categories were previously identified as the paths of least resistance in the egg task (Agogué et al., in press). Our results are consistent with those obtained previously with several groups of adults, including undergraduate students, engineers, industrial designers and entrepreneurs (Agogué, Poirel, et al., 2014). By contrast, children generated fewer ideas related to “slowing the fall” using a parachute, for example, which suggests that this design heuristic is less accessible and thus less explored by children than by adults. The specificity of the nature of the fixation effect observed in children during Section 2 was replicated with the control group of children in Section 4, confirming the robustness of the findings reported by Agogué, Poirel, et al. (2014).

The major question in Section 4 was whether providing an example of a solution to participants before solving the egg task would have an opposite effect on the generation of creative ideas in children and adults, given that the example chosen was within the fixation effect for adults and outside the fixation effect for children. The results for the control groups showed that adults outperformed children with regard to fluency and flexibility, which is consistent with previous developmental investigations reporting the facilitation of divergent thinking with age (Jaquish & Ripple, 1980; Kleibeuker, Koolschijn, Jolles, De Dreu, Crone, 2013; Wu et al., 2005), although some recent work has shown similar developmental changes only for originality measures (Kleibeuker, De Dreu, et al., 2013). Although the children in the control group proposed fewer solutions and fewer categories of solutions than the adults in the control group, the introduction of an example before the creative task appears to have dramatically modified this developmental pattern. As expected, our results show that exposure to the same example has two opposite effects on adults and children: adults are constrained in their ability to propose solutions, whereas this ability is enhanced for children in terms of fluency and flexibility. This beneficial effect of providing an example for children allowed them to reach adult-like levels of performance for both the number of solutions and the number of categories proposed. Critically, an analysis of the originality scores for each age group separately revealed that the introduction of an example stimulated the ability to propose original solutions in children, whereas this same example had a negative influence on creativity in adults.

Given the differences in the fixation effects between adults and children, our results provide additional support for the hypothesis that the effect of examples on idea generation depends on whether the examples are within or outside the fixation effect. Examples within the fixation effect (as was the case for the adults) reduced the participants’ ability to propose original solutions, whereas examples outside the fixation effect (as was the case for the children) increased generation processes (Bonnardel & Marmeche, 2004; Bonnardel & Zenasni, 2007). Nevertheless, the qualitative analysis of the responses proposed by children who were exposed to examples indicated that they considered solutions belonging to the meta-category of “slowing the fall” more strongly than those in the control group did spontaneously. Thus, providing examples outside the fixation effect did not stimulate the ability of children to generate solutions across various categories; rather, it may have caused an increase in in-depth consideration of the proposed solution. In accordance with the “path of least resistance” model (Smith et al., 1995), our findings suggest that the introduction of an example in the present study triggered the activation of knowledge that was less spontaneously accessible for children, allowing them to propose a greater quantity and variety of ideas in the primed category.

A possible limitation of the current study is that participants were not allowed to draw, or to include also drawings besides the verbal description of the solutions in the egg task. Given that describing the solutions in a pictorial way might influence the ability to overcome fixation effect in the egg task, further work will be necessary to investigate this question.

6. Conclusion

In conclusion, our results clearly demonstrate that external clues, such as an example of a solution, can have a stimulating effect on the quantity and variety of ideas proposed by children to solve a design problem. Therefore, providing an example to children increases their in-depth consideration of ideas related to the proposed solution, which allows them to reach adult-like levels of performance with regard to fluency and flexibility.

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Title of the Presentation:

Towards generative models in AI

Synopsis:

We first review the state of the art of generativity in data science, distinguishing works on "sample" generation (adversarial example, out-of-class novelty generation) and model exploration and generation (so called generative design or rather 'multi-objective genetic algorithm, novelty search & map elite,…). In a second part we give hints on how to develop generative models in AI and statistics. We illustrate this with two papers: design theory applied to statistical decision making, design theory applied to models of independances for the analysis of data on functional expansion.

Main References:

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OUT-OF-CLASS NOVELTY GENERATION: AN EXPERIMENTAL FOUNDATION

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ABSTRACT

Recent advances in machine learning have brought the field closer to computational creativity research. From a creativity research point of view, this offers the potential to study creativity in relationship with knowledge acquisition. From a machine learning perspective, however, several aspects of creativity need to be better defined to allow the machine learning community to develop and test hypotheses in a systematic way. We propose an actionable definition of creativity as the generation of out-of-distribution novelty. We assess several metrics designed for evaluating the quality of generative models on this new task. We also propose a new experimental setup. Inspired by the usual held-out validation, we hold out entire classes for evaluating the generative potential of models. The goal of the novelty generator is then to use training classes to build a model that can generate objects from future (hold-out) classes, unknown at training time - and thus, are novel with respect to the knowledge the model incorporates. Through extensive experiments on various types of generative models, we are able to find architectures and hyperparameter combinations which lead to out-of-distribution novelty.

1 INTRODUCTION

Recent advances in machine learning have renewed interest in artificial creativity. Studies such as deep dream (Mordvintsev et al., 2015) and style transfer (Gatys et al., 2015) have aroused both general public interest and have given strong impetus to use deep learning models in computational creativity research (ICC, 2016). Although creativity has been a topic of interest on and off throughout the years in machine learning (Schmidhuber, 2009), it has been slowly becoming a legitimate sub-domain with the appearance of dedicated research groups such as Google's Magenta and research work on the topic (Nguyen et al., 2015; Lake et al., 2015).

There is a large body of work studying creativity by computational methods. A large variety of techniques, from rule-based systems to evolutionary computation has been used for a myriad of research questions. Compared to these methods, machine learning methods provide an important advantage: they enable the study of creativity in relation with knowledge (i.e., knowledge-driven creativity; Kazakçı et al. (2016b)). Nevertheless, to better highlight the points of interest in computational creativity research for the machine learning community and to allow machine learning researchers to provide systematic and rigorous answers to computational creativity problems, it is important to precisely answer three questions:

1. What is meant by the generation of novelty?
2. How can novelty be generated?
3. How can a model generating novelty be evaluated?

Within the scope of machine learning, it would be tempting to seek answers to these questions in the sub-field on generative modeling. Mainstream generative modeling assumes that there is a phenomena generating the observed data and strive to build a model of that phenomena, which would, for instance, allow generating further observations. Traditional generative modeling considers only *in-distribution* generation where the goal is to generate objects from the category or categories of already observed objects. In terms of novelty generation, this can be considered as generating look-a-likes of known *types* of objects. Although there is considerable value in in-distribution generation (e.g., for super-resolution (Freeman et al., 2002; Dong et al., 2014; Ledig et al., 2016) or in-painting (Xie et al., 2012; Cho, 2013; Yeh et al., 2016)), this perspective is limited from a strict point of view of creativity: it is *unlikely* to come up with a *flying ship* by generating samples from a distribution of *ships* and *flying objects*.

Researchers in creativity research (Runco & Jaeger, 2012) have argued that the crux of creative process is the ability to build new categories based on already known categories. However, creativity is beyond a simple combination exploration: it is about generating previously unknown but meaningful (or valuable) new types of objects using previously acquired knowledge (Hatchuel & Weil, 2009; Kazakçı, 2014). Under this perspective, novelty generation aims at exhibiting an example from a new type. This objective, which we shall call *out-of-distribution generation*, is beyond what can be formalized within the framework of traditional learning theory, even though learning existing types is a crucial part of the process.

From a machine learning point of view, generating an object from an unknown type is not a well-defined problem, and research in generative modeling usually aims at *eliminating* this possibility altogether, as this is seen as a source of instability (Goodfellow et al., 2014; Salimans et al., 2016) leading to spurious samples (Bengio et al., 2013). In a way, sampling procedures are designed to kill any possibility of sampling out of the distribution, which is a problem for studying the generation of novelty by machine learning methods.

Arguably, the most important problem is the evaluation of what constitutes a good model for generating out-of-distribution. On the one hand, we are seeking to generate *meaningful* novelty, not trivial noise. On the other hand, we aim at generating *unknown* objects, so traditional metrics based on the concept of likelihood are of no use since novelty in the out-of-distribution sense is unlikely by definition. This lack of metrics hinders answering the first two questions. Without a clear-cut evaluation process, the utility of extending the definition of novelty generation to out-of-sample seems pointless.

This paper argues that for a wider adoption of novelty generation as a topic for scientific study within machine learning, a new engineering principle is needed, which would enable such evaluation, and consequently, rigorous experimental research. In the traditional supervised context, the main engineering design principle is the minimization of the error on a hold-out test set. The paper proposes a simple setup where the generative potential of models can be evaluated by *holding out entire classes*, simulating thus unknown but meaningful novelty. The goal of the novelty generator is then to use training classes to build a model that can generate objects from future (hold-out) classes, unknown at training time.

The main contributions of this paper:

- We design an experimental framework based on hold-out classes to develop and to analyze out-of-distribution generators.
- We review and analyze the most common evaluation techniques from the point of view of measuring out-of-distribution novelty. We argue that likelihood-based techniques inherently limit exploration and novelty generation. We carefully select a couple of measures and demonstrate their applicability for out-of-distribution novelty detection in experiments.
- We run a large-scale experimentation to study the ability of novelty generation of a wide set of different autoencoders and GANs. The goal here is to re-evaluate existing architectures under this new goal in order to open up exploration. Since out-of-distribution novelty generation is arguably a wider (and softer) objective than likelihood-driven sampling from a fixed distribution, existing generative algorithms, designed for this latter goal, constitute a small subset of the algorithms able to generate novelty. The goal is to motivate the reopening some of the closed design questions.

The paper is organized as follows. We review some of the seminal work at the intersection of machine learning and out-of-distribution generation in Section 2. We discuss the conceptual framework of out-of-distribution generation and its relationship with likelihood-based generative models in Section 3. We outline the families of evaluation metrics, focusing on those we use in the paper in Section 4. In Section 4.3 we describe the gist of our experimental setup needed to understand the metrics described in Section 4.4, designed specifically for the out-of-distribution setup. We describe the details of the experimental setup and analyze our results in Section 5. Finally, we conclude in Section 6.

2 MACHINE LEARNING AND NOVELTY GENERATION: THE INNOVATION ENGINE, "ZERO-SHOT" LEARNING, AND DISCOVERING NEW TYPES

There are three important papers that consider novelty generation in a machine learning context. Nguyen et al. (2015) propose an innovation engine (Figure 1(a)). They generate images using a neural net that composes synthetic features. The generator is fed back with an entropy-based score (similar to objectness; Section 4.2) coming from an Imagenet classifier, and the feedback is used in an evolutionary optimization loop to drive the generation. An important contribution of the paper is to demonstrate the importance of the objectness score. They show that interesting objects are not generated when asking the machine to generate from a single given class. The generation paths often go through objects from different classes, "stepping stones" which are seemingly unrelated to the final object. The main conceptual difference between our approaches is that Nguyen et al. (2015) do not ground their generative model in learned knowledge: their generation process is not learned model, rather a stochastic combinatorial engine. On the one hand, this makes the generation (evolutionary optimization) rather slow, and on the other, the resulting objects reflect the style of the (preset) synthetic features rather than features extracted from existing objects.

The main goal of Lake et al. (2015) and Rezende et al. (2016) is *one-shot learning and generation*: learn to classify objects given a small number (often one) of examples coming from a given category, and learn to generate new objects given a single example (Figure 1(b)). One-shot generation is definitely an intermediate step towards out-of-distribution generation. The extremely low number of examples conceptually limits likelihood-based learning/fitting/generation. Lake et al. (2015) circumvents this problem by learning strong Bayesian top-down models (programs) that capture the structural properties of known objects which are generalizable across classes. They also consider unconstrained ("zero-shot") generation as an extension of their approach, and show that the model can generate new symbols from scratch. They make no attempt to conceptualize the goal of unconstrained generation outside the top-down Bayesian framework, or to design evaluation metrics to assess the quality of these objects, but their intriguing results are one of the strongest motivations of our paper.

Kazakçı et al. (2016a) show that symbols of new types can be generated by carefully tuned autoencoders, learned entirely bottom-up, without imposing a top-down Bayesian architecture (Figure 1(c)). They also make a first step of defining the conceptual framework of novelty generation by arguing the goal of generating objects from new *types*, unknown at the time of training. They design a technique for finding these new types semi-automatically (combining clustering and human labeling). They argue the importance of defining the *value* of these new types (and of out-of-distribution generation in general), but they make no attempt to design evaluation metrics, thus limiting the exploration and the development of out-of-distribution generative architectures.

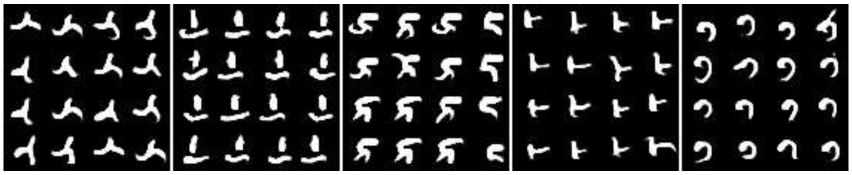
3 PROBABILISTIC VS. CONSTRUCTIVE GENERATIVE MODELS

The generative process is commonly framed in a probabilistic setup: it is assumed that an underlying unknown likelihood *model* $\mathcal{P}(\cdot)$ should first be learned on an i.i.d. *training* sample $\mathcal{D} = \{\mathbf{x}_1, \ldots, \mathbf{x}_n\}$, assumed to be generated from $\mathcal{P}(\cdot)$, and then a *sampler* $\mathcal{S}$ should sample from the learned $\widehat{\mathcal{P}}(\cdot)$. The first step, estimating $\mathcal{P}(\cdot)$ using $\mathcal{D}$, is a classical function learning problem that can be studied through the usual concepts of overfitting and regularization, and algorithms can be designed using the classical train/test principle. The second step, designing $\mathcal{S}$ for sampling from $\widehat{\mathcal{P}}(\cdot)$ is also a classical domain of random sampling with a conceptual framework and a plethora of methods.

Technically both steps are notoriously hard for the high-dimensional distributions and the complex dependencies we encounter in interesting domains. Hence, most of the recent and successful methods get rid of the two-step procedure at the level of algorithmic design, and short-cut the procedure from the probabilistic $\mathcal{D} \to \mathcal{P} \to \mathcal{S}$ to the constructive $\mathcal{D} \to \mathcal{A}$, where $\mathcal{A}(\mathcal{D})$ is a *generator*, tasked to produce sample objects *similar* to elements of $\mathcal{D}$ but *not identical* to them. $\mathcal{A}$ is fundamentally

(a) "Synthetic" objects from imagenet categories from Figure 7 of Nguyen et al. (2015)

(b) "Unconstrained" symbols from Figure 7 of Lake et al. (2015)



(c) New types of symbols from Figure 6 of Kazakçı et al. (2016a)

Figure 1: Examples of generating new objects or types.

different from $(\mathcal{P}, \mathcal{S})$ in that there is no explicit fitting of a *function*, we use $\mathcal{D}$ to directly *design an algorithm* or a *program*.

When the probabilistic setup is still kept for *analysis*, we face a fundamental problem: if we assume that we are given the true likelihood function $\mathcal{P}(\cdot)$, the likelihood of the training sample $\frac{1}{n}\sum_{i=1}^{n}\log\mathcal{P}(\mathbf{x}_i)$ is a random variable drawn independently from the distribution of log-likelihoods of i.i.d. samples of size n, so the trivial generator $\mathcal{A}$ which *resamples* $\mathcal{D}$ will have the same expected log-likelihood as an optimal i.i.d. sampler. The resampling "bug" is often referred to as "overfitting". While it makes perfect sense to talk about overfitting in the $\mathcal{D} \to \mathcal{P} \to \mathcal{S}$ paradigm (when $\mathcal{P}$ is *fitted* on $\mathcal{D}$), it is somewhat conceptually misleading when there is no fitting step, we propose to call it "memorizing". When a generator $\mathcal{A}$ is trained on $\mathcal{D}$ without going through the fitting step $\mathcal{D} \to \mathcal{P}$, the classical tools for avoiding memorizing (regularization, the train/test framework) may be either conceptually inadequate or they may not lead to an executable engineering design principle.

The conceptual problem of analyzing constructive algorithms in the probabilistic paradigm is not unrelated to our argument of Section 1 that the probabilistic generative framework is too restrictive for studying novelty generation and for designing out-of-distribution generative models. In our view, this flaw is not a minor nuisance which can be fixed by augmenting the likelihood to avoid resampling, rather an inherent property which cannot (or rather, should not) be fixed. The probabilistic framework is designed for generating objects from the distribution of known objects, and this is in an axiomatic contradiction with generating out-of-distribution novelty, objects that are *unknown* at the moment of assembling a training sample. Resampling (generating *exact* copies) is only the most glaring demonstration of a deeper problem which is also present in a more subtle way when attempting to generate new *types* of objects.

We are not arguing that the probabilistic generative framework should be banished, it has a very important role in numerous use cases. Our argument is that it is not adequate for modeling out-of-distribution novelty generation. What follows from this on the *algorithmic* level is not revolutionary: the design of most successful generative algorithms already moved beyond the probabilistic framework. On the other hand, moving beyond the probabilistic generative framework at a *conceptual* level is a paradigm change which will require groundwork for laying the foundations, including revisiting ideas from a domain larger than machine learning.

At the algorithmic/computational level the machine learning community has already started to move beyond likelihood. The overfitting problem is often solved by implicitly constraining $\mathcal{A}$ not to resample. Another common solution is to design tractable likelihood surrogates that implicitly penalize memorization. These surrogates then can be used at the training phase (to obtain non-resampling generators explicitly) and/or in the evaluation phase (to eliminate generators that resample). The ingenious idea of using discriminators in GANs (Goodfellow et al., 2014; Salimans et al., 2016) is a concrete example; although the setup *can* be analyzed through the lens of probabilistic sampling, one does not *have to* fall back onto this framework. If we drop the underlying conceptual *probabilistic* framework, the *constructive* GAN idea may be extended beyond generating from the *set* which is indistinguishable from the set of existing objects. In Section 4.4 we will use discriminators to assess the quality of generators whose very goal is to generate novelty: objects that *are* distinguishable from existing objects. The main challenge is to avoid the trivial novelty generator, producing uninteresting noise. This challenge is structurally similar to avoiding the trivial memorizing/resampling generator in in-distribution sampling. The two main elements that contribute to the solution is i) to ground the generator strongly in the structure of existing *knowledge*, without overly fixating it on existing *classes*, and ii) use a discriminator which knows about *out-of-class* novelty to steer architectures towards novelty generation.

4 EVALUATION OF GENERATIVE MODELS

In this section we outline the families of evaluation metrics, focusing on those we use in the paper. In Section 4.3 we describe the gist of our experimental setup needed to understand the metrics described in Section 4.4, designed specifically for the out-of-distribution setup.

4.1 INDIRECT SUPERVISED METRICS

When generative models are used as part of a pipeline with a supervised goal, the evaluation is based on the evaluation of the full pipeline. Examples include unsupervised pre-training (Hinton et al. (2006); Bengio et al. (2007); the original goal that reinvigorated research in neural nets), semi-supervised learning (Kingma et al., 2014; Rasmus et al., 2015; Maaløe et al., 2016; Salimans et al., 2016), in-painting (Xie et al., 2012; Cho, 2013; Yeh et al., 2016), or super-resolution (Freeman et al., 2002; Dong et al., 2014; Ledig et al., 2016). The design goal becomes straightforward, but the setup is restricted to improving the particular pipeline, and there is no guarantee that those objectives can be transferred between tasks. In our case, the objective of the supervised pipeline may actually suppress novelty. In a certain sense, GANs also fall into this category: the design goal of the generator is to fool a high-quality discriminator, so the generator is asked *not* to generate new objects which can be easily discriminated from known objects. In our experiments, surprisingly, we found that GANs can be still tuned to generate out-of-distribution novelty, probably due to the deficiencies of both the generator and the discriminator. Our goal in this paper can also be understood as designing a pipeline that turns novelty generation into a supervised task: that of generating objects from classes unknown at training time.

4.1.1 PARZEN DENSITY ESTIMATOR

Parzen density estimators are regularly used for estimating the log-likelihood of a model (Breuleux et al., 2009). A kernel density estimator is fit to generated points, and the model is scored by log-likelihood of a hold-out test set under the kernel density. The metrics can be easily fooled (Theis et al., 2015), nevertheless, we adopted it in this paper for measuring both the in-distribution and out-of-distributions quality of our generators.

4.2 OBJECTNESS

Salimans et al. (2016) proposed a new entropy-based metrics to measure the “objectness”[1] of the generated *set* of objects. As GANs, the metrics uses a trained discriminator, but unlike GANs, it is not trained for separating real objects and generated objects, rather to classify real objects into existing categories. The goal of the generator is create objects which belong confidently to a low number (typically one) of classes. To penalize generators fixating onto single objects or categories, they also require that the *set* of objects has a high entropy (different objects span the space of the categories represented by the discriminator). The metrics is only indirectly related to classical log-likelihood: in a sense we measure how likely the objects are *through the “eye” of a discriminator*.

Formally, objectness is defined as

$$\frac{1}{N}\sum_{i=1}^{n}\sum_{\ell=1}^{K} p_{i,\ell} \log \frac{p_{i,\ell}}{p_\ell},$$

---

[1] They also call it “inception score” but we found the term objectness better as it is more general than the single model used in their paper.

where K is the number of classes,

$$p_{i,\ell} = \mathcal{p}(\ell|\mathbf{x}_i)$$

is the posterior probability of category ℓ given the generated object $\mathbf{x}_i$, under the discriminator $\mathcal{p}$ trained on a set with known labels, and

$$p_\ell = \frac{1}{n}\sum_{i=1}^{n} p_{i,\ell},$$

are the class marginals.

Salimans et al. (2016) proposed this metric as one of the "tricks" to stabilize GANs, but, interestingly, a similar measure was also used in the context if evolutionary novelty generation (Nguyen et al., 2015).

4.3 ASSESSING OUT-OF-DISTRIBUTION NOVELTY BY OUT-OF-CLASS SCORING

As the classical supervised validation setup simulates past (training) and future (test) by randomly partitioning an existing data set, we can simulate existing knowledge and novelty by partitioning existing data sets *holding out entire classes*. The goal of the novelty generator is then to use training classes to build a model that can generate objects from future (hold-out) classes, unknown at training. In our first experiments we tried to leave out single classes of MNIST, but the label noise "leaked" hold-out classes which made the evaluation tricky. To avoid this, we decided to challenge the generator, trained on MNIST, to generate *letters*. We pre-trained various discriminators using different setups, only on digits (MNIST), only on letters (Google fonts), or on a mixture of digits and letters, and used these discriminators to evaluate novelty generators in different ways. For example, we measure *in-class objectness* and *in-class Parzen* using a discriminator trained on MNIST, and *out-of-class objectness* and *out-of-class Parzen* by a discriminator trained on (only) Google fonts.

4.4 OUT-OF-CLASS SCORES

Naturally, letter discriminators see letters everywhere. Since letters are all they know, they classify everything into one of the letter classes, quite confidently (this "blind spot" phenomenon is exploited by Nguyen et al. (2015) for generating "synthetic" novelty), the letter objectness of an in-distribution digit generator can sometimes be high. For example, a lot of *6*s were classified as *b*s. To avoid this "bias", we also trained a discriminator on the union of digits and letters, allowing it to choose digits when it felt that the generated object looked more like a digit. We designed two metrics using this discriminator: *out-of-class count* measures the frequency of confidently classified letters in a generated set, and *out-of-class max* is the mean (over the set) of the probability of the most likely letter. None of these metrics penalize "fixated" generators, outputting the same few letters all the time, so we combine both metrics with the entropy of the letter posterior (conditioned on being a letter).

Formally, let $p_{i,1}, \ldots, p_{i,K_{\text{in}}}$ be the in-class posteriors and $p_{i,K_{\text{in}}+1}, \ldots, p_{i,K_{\text{in}}+K_{\text{out}}}$ be the out-of-class posteriors, where $K_{\text{in}} = 10$ is the number of in-class classes (digits), and $K_{\text{out}} = 26$ is the number of out-of-class classes (letters). Let

$$\ell_i^* = \arg\max_{\ell} p_{i,\ell}$$

and

$$\ell_{\text{out}\,i}^* = \underset{K_{\text{in}}<\ell\leq K_{\text{in}}+K_{\text{out}}}{\arg\max} p_{i,\ell}$$

be the most likely category overall and most likely out-of-class category, respectively. Let

$$\tilde{p}_\ell = \frac{\sum_{i=1}^{n} \mathbb{I}\left\{\ell = \ell_{\text{out}\,i}^*\right\}}{\sum_{i=1}^{n} \mathbb{I}\left\{\ell_{\text{out}\,i}^* > K_{\text{in}}\right\}}$$

be the normalized empirical frequency of the out-of-class category ℓ. We measure the diversity of the generated sample by the normalized entropy of the empirical frequencies

$$\text{diversity} = -\frac{1}{\log K_{\text{out}}} \sum_{\ell=K_{\text{in}}}^{K_{\text{in}}+K_{\text{out}}} \tilde{p}_\ell \log \tilde{p}_\ell,$$

and define

$$\text{out-of-class count} = (1-\lambda) \times \frac{1}{n}\sum_{i=1}^{n} \mathbb{I}\left\{\ell_i^* > K_{\text{in}} \wedge p_{i,\ell_i^*} > \theta\right\} + \lambda \times \text{diversity},$$

and

$$\text{out-of-class max} = (1-\lambda) \times \frac{1}{n}\sum_{i=1}^{n} p_{i,\ell^*_{\text{out}\,i}} + \lambda \times \text{diversity}.$$

In our experiments we set the confidence level $\theta = 0.95$ and the mixture coefficient $\lambda = 0.5$.

4.5 HUMAN REFEREEING AND THE VISUAL TURING TEST

The ultimate test of l'art pour l'art generative models is whether humans like the generated objects. Visual inspection is often used as an evaluation principle in papers (Denton et al., 2015; Radford et al., 2015; Dosovitskiy et al., 2016), and it is sometimes even made part of the objectified pipeline by using crowdsourcing tools (Denton et al., 2015; Lake et al., 2015; Salimans et al., 2016). First, it definitely makes development (e.g., model selection and hyperparameter tuning) slow. Second, the results depend a lot on what questions are asked and how the responders are primed. For testing generative models, the usual GAN-type question to ask is whether the generated objects are generated by a nature (or a human) or a machine (the visual Turing test). Even those that go the furthest in tasking machines to generate novelty (Lake et al., 2015) ask human judges to differentiate between human and machine. In our view, this question is too restrictive when the goal is out-of-distribution novelty generation. Asking whether an object is "new" is arguably too vague, but inventing adjective categories (such as "surprising" or "interesting" (Schmidhuber, 2009)) that can poll our ability to detect novelty should be on the research agenda. Priming is another important issue: the answer of a human annotator can depend on the information given to her. Nevertheless, a human annotation tool with well-designed priming and questions could accelerate research in novelty generation in the same way labeling tools and standard labeled benchmark sets accelerated supervised learning.

We assessed the visual quality of the set of generated objects using an in-house annotation tool. We took each model which appeared in the top ten by any of the quantitative metrics described in the previous section, and hand-labeled them into one of the following three categories: i) letters, ii) digits, and iii) bad sample (noise or not-a-symbol).

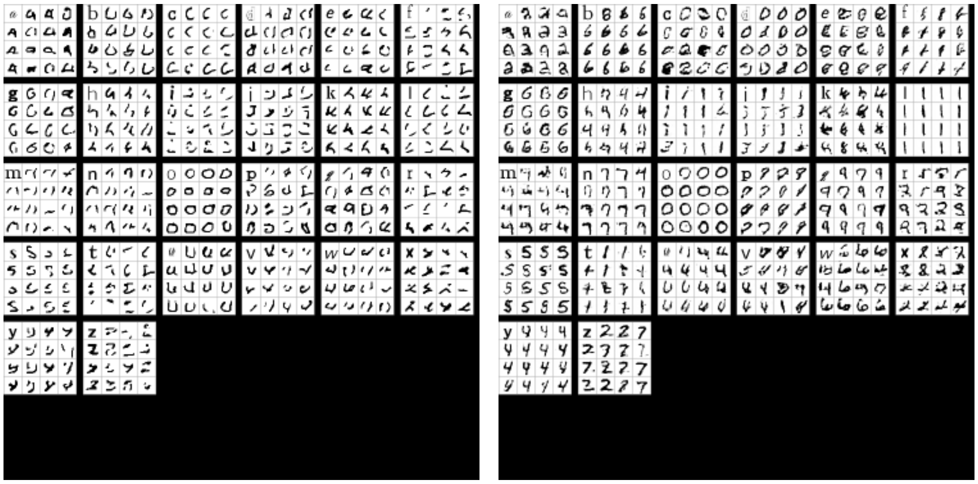
Each panel consisted 26×15 generated objects, the fifteen most probable symbols of each letter according to the classifier trained on both letters and digits (Figure 2). The goal of this annotation exercise was i) to assess the visual quality of the generated symbols and ii) to assess the quality of the metrics in evaluating novelty.

5 EXPERIMENTS

Our scores cannot be directly optimized because they all measure out-of-class performance, and showing out-of-class objects at training would be "cheating". All our (about 1000) models were trained for "classical" objectives: reconstruction error in the case of autoencoders, and adversarial error in the case of GANs. The out-of-class scores were used as a weak feedback for model selection and (quasi random) hyperparameter optimization. The goal is not to be statistically flawless, after all we do not have a statistical model. Rather we set our goal to analyze existing generative architectures from the point of view of novelty generation. Most of the generative models come from a large class of architectures, sometimes purposefully designed for not to "misbehave". When possible, we turned these tricks, designed to avoid generating "spurious" objects, into optional hyperparameters.

5.1 DETAILED EXPERIMENTAL SETUP

We used two families of deep learning based generative models, autoencoders and GANs. The architectures and the optional features are described in the next sections. All hyperparameters were selected randomly using reasonable priors. All the $\sim$1000 autoencoders were trained on MNIST training data.



(a) The top autoencoder (b) The top GAN

Figure 2: A couple of the top models according to human assessment. Top left characters of each 4×4 panel are the labels, letters coming from the training sample. For each letter we display the fifteen most probable symbols according to the classifier trained on both letters and digits.

5.1.1 AUTOENCODER ARCHITECTURES AND GENERATION PROCEDURE

We used three regularization strategies for autoencoders: sparse autoencoders (Makhzani & Frey, 2013; 2015), denoising autoencoders (Bengio et al., 2013) and contractive autoencoders (Rifai et al., 2011).

Sparse autoencoders can either be fully connected or convolutional. For fully connected sparse autoencoders, we use the k-sparse formulation from Makhzani & Frey (2013), a simple way of obtaining a sparse representation by sorting hidden units and keeping only the top $k\%$, zeroing out the others, and then backpropagating only through non-zero hidden units.

For convolutional sparse architectures, we use the “winner take all” (WTA) formulation from Makhzani & Frey (2015) which obtains *spatial sparsity* in convolutional feature maps by keeping only the maximum activation of each feature map, zeroing out the others. We optionally combine it with *channel sparsity* which, for each position in the feature maps, keeps only the maximum activation across the channels and zero out the others.

For contractive autoencoders, we use the fully connected version with a single hidden layer from Rifai et al. (2011).

We also explore mixtures between the different autoencoder variants in the hyperparameter search. For each model we choose to enable or disable independently the denoising training procedure, the contractive criterion (parametrized by the contractive coefficient, see (Rifai et al., 2011)) and the sparsity rate k (only for fully connected architectures). Table 1 shows the hyperparameters and their priors

The generation procedure we use for autoencoders is based on Bengio et al. (2013), who proposed a probabilistic interpretation of denoising autoencoders and a way to sample from them using a Markov chain. To have a convergent procedure and to obtain fixed points, we chose to use a deterministic generation procedure instead of a Markov chain (Bahdanau & Jaeger, 2014). As in Bahdanau & Jaeger (2014), we found that the procedure converged quickly.

In initial experiments we found that 100 iterations were sufficient for the majority of models to have convergence so we chose to fix the maximum number of iterations to 100. We also chose to extend the procedure of Bahdanau & Jaeger (2014) by binarizing (using a threshold) the images after each reconstruction step, as we found that it improved the speed of the convergence and could lead to final samples with an exact zero reconstruction error.

For stochastic gradient optimization of the autoencoder models, we used adadelta (Zeiler, 2012) with a learning rate of 0.1 and a batch size of 128. We used rectified linear units as an activation function for hidden layers in all models. We use the sigmoid activation function for output layers.

Table 1: Autoencoder hyperparameters priors

Name	Prior	Type
nb layers	1, 2, 3, 4, 5	choice
nb fully connected hidden units	100,200,300,...1000	choice
nb conv layers	1, 2, 3, 4, 5	choice
nb conv filters	8, 16, 32, 64, 128, 256, 512	choice
conv layers filter size	3 or 5	choice
noise corruption	[0, 0.5]	uniform
k sparsity rate	[0, 1]	uniform
contraction coefficient	[0, 100]	uniform

5.1.2 GENERATIVE ADVERSARIAL NETWORKS (GANS)

For GANs, we built upon Radford et al. (2015) and used their architecture as a basis for hyperparameter search. We modified the code proposed here to sample new combinations of hyperparameters. Table 2 shows the hyperparameters and their priors.

Name	Prior	Type
nb discr. updates	1, 2, 3	choice
l2 coeficient	$[10^{-6}, 10^{-1}]$	logspace
gen. input dim.	10, 20, 50, 70, 100, 150, 200, 300	choice
nb fully connected gen. units	8, 16, 32, 64, 128, 256, 1024, 2048	choice
nb fully connected discr. units	8, 16, 32, 64, 128, 256, 1024, 2048	choice
nb filters gen.	8, 16, 32, 64, 128, 256, 512	choice
nb filters discr.	8, 16, 32, 64, 128, 256, 512	choice
nb iterations	50, 100, 150, 200, 250, 300	choice
learning rate	$[10^{-6}, 10^{-1}]$ on logspace, or 0.0002	logspace
weight initialization	Normal(0, std) where std is from $[10^{-3}, 10^{-1}]$	logspace

Table 2: GAN hyperparameters priors

5.1.3 GENERATIVE ADVERSARIAL NETWORKS (GANS)

5.2 ANALYSIS

First, we found that tuning (selecting) generative models for in-distribution generation will make them “memorize” the classes they are trained to sample from. This is of course not surprising, but it is important to note because it means that out-of-class generation is non-trivial, and the vast majority of architectures designed and tuned in the literature are not generating out-of-class novelty naturally. Second, we did succeed to find architectures and hyperparameter combinations which lead to out-of-class novelty. Most of the generated objects, of course, were neither digits nor letters, which is why we needed the “supervising” discriminators to find letter-like objects among them. The point is not that *all* new symbols are letters, that would arguably be an impossible task, but to demonstrate that by opening up the range of generated objects, we do not generate noise, rather objects that *can be* forming new categories.

The quantitative goal of this study was to assess the quality of the defined *metrics* in evaluating out-of-distribution generators. We proceeded in the following way. We selected the top ten autoencoders and GANs according to the five metrics of out-of-class (letters) count, out-of-class max, out-of-class objectness, out-of-class Parzen, and in-class Parzen. We then annotated these models into one of the three categories of “letter” (out), “digit” (in), and “bad” (noise or not-a-symbol). The last three columns of Table 3 show that the out-of-class count and out-of-class max scores work well in selecting good out-of-class generators, especially with respect to in-class generators. They are

	inter-score correlations								human counts		
	oc	om	oo	op	ic	im	io	ip	out	in	bad
out count	1	-0.03	-0.13	0.04	-0.12	0.02	-0.07	-0.11	12	0	8
out max	-0.03	1	-0.07	0.01	-0.16	-0.10	0.03	-0.09	15	0	5
out objectness	-0.13	-0.07	1	0.21	-0.06	0.08	0.02	-0.08	9	10	1
out Parzen	0.04	0.01	0.21	1	-0.17	0.01	-0.19	-0.20	4	13	3
in count	-0.12	-0.16	-0.06	-0.17	1	0.30	0.1	0.14	-	-	-
in max	0.02	-0.10	0.08	0.01	0.30	1	0.03	0.06	-	-	-
in objectness	-0.07	0.03	0.02	-0.19	0.1	0.03	1	0.00	-	-	-
in Parzen	-0.11	-0.09	-0.08	-0.20	0.14	0.06	0.00	1	0	17	3

Table 3: Inter-score correlations among top 10% models per score and human annotation counts among top twenty models per score. out=letters; in=digits.

relatively bad in selecting good generators overall. Symmetrically, out-of-class objectness and the Parzen measures select, with high accuracy, good quality models, but they mix out-of-class and in-class generators (digits and letters). Parzen scores are especially bad at picking up good out-of-class generators. Somewhat surprisingly, even out-of-class Parzen is picking digits, probably because in-distribution digit generators generate more regular, less noisy images than out-of-class letter generators. In other words, opening the space towards non-digit like "spurious" symbols come at a price of generating less clean symbols which are farther from letters (in a Parzen sense) than clean digits.

We also computed the inter-score correlations in the following way. We first selected the top 10% models for each score because we were after the correlation of the best-performing models . Then we computed the Spearman rank correlation of the scores (so we did not have to deal with different scales and distributions). The first eight columns of Table 3 show that i) in-class and out-of-class measures are anti-correlated, ii) out-of-class count and max are uncorrelated, and are somewhat anti-correlated with out-of-class objectness.

These results suggest that the best strategy is to use out-of-class objectness for selecting good quality models and out-of-class count and max to select models which generate letters. Figure 3 illustrate the results by pangrams (sentences containing all letters) written using the symbols generated. The models (a)-(d) were selected automatically: these were the four models that appeared in the top ten both according to out-of-class objectness and out-of-class counts. Letters of the last sentence (e) were hand-picked by us from letters generated by several top models. Among the four models, three were fully connected autoencoders with sparsity and one was a GAN. All of the three sparse autoencoders had five hidden layers and used a small noise corruption (less than 0.1). The GAN used the default learning rate of 0.0002 and a large number (2048) of fully connected hidden units for the generator, while the number of fully connected hidden units of the discriminator was significantly smaller (128).

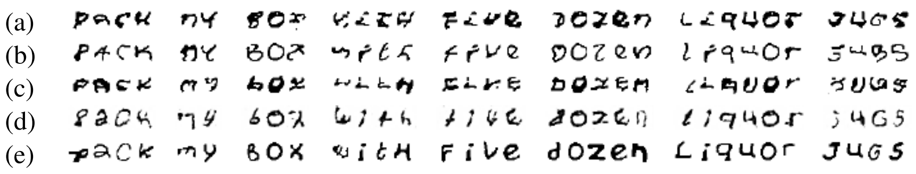


Figure 3: Pangrams created (a-d) using top models selected automatically, and (e) using letters selected from several models by a human.

6 DISCUSSION AND PERSPECTIVES

In this paper we have proposed a framework for designing and analysing generative models for novelty generation. The quantitative measures make it possible to systematically study the creative capacity of generative models. We believe that human evaluation will remain an important source of feedback in this domain for the foreseeable future. Nevertheless, quantitative measures, such as our out-of-class objectness and out-of-class count and max, will i) make it possible to semi-automate the search for models that exhibit creativity, and ii) allow us to study, from the point of view of novelty generation, the numerous surrogates used for evaluating generative models (Theis et al., 2015), especially those that explicitly aim at quantifying creativity or interestingness (Schmidhuber, 2009).

The main focus of this paper was setting up the experimental pipeline and to analyze various quality *metrics*, designed to measure out-of-distribution novelty of samples and generative models. The immediate next goal is to analyze the *models* in a systematic way, to understand what makes them "memorizing" classes and what makes them opening up to generate valuable out-of-distribution samples.

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A LAW OF FUNCTIONAL EXPANSION - ELICITING THE DYNAMICS OF CONSUMER GOODS INNOVATION WITH DESIGN THEORY

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ABSTRACT

For more than two decades, mobile phone industry has shown that innovation is not only functional optimization and combination but can also be a "functional expansion”. Sometimes called radical or disruptive innovation, this phenomenon leads to the development of new method for engineers and designers. However, the intensity remains undemonstrated: is functional expansion a rare phenomenon (few products during very short periods of time) – or is it an intense phenomenon, that even might have accelerated in the last decades? To answer these questions, the paper overcomes two main obstacles: how to measure functional expansion? And what would be a law of functional expansion, that would enable to test the importance and newness of the phenomena? Building on recent advances on the measurement of innovation and on new computational models of design derived from most advanced design theories, this paper presents unique data on functional expansion of 8 consumer products and tests that functional expansion significantly accelerated in the mid 1990s. The paper confirms quantitatively that our societies are now in a new design regime, a regime of innovative design.

Keywords: Design theory, Innovation, Functional expansion, Technology

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1 INTRODUCTION

For more than two decades, mobile phone industry has shown that innovation is not only functional optimization and combination but can also be a "*functional expansion*", ie it consists in regularly, repeatedly *inventing new functions for products*: over the last decades, the phone became a 'smart phone' with surprising new functions. This phenomenon of functional expansion is also analysed as 'disruptive innovation' (Christensen 1993, 1997) or 'radical innovation' (O'Connor 1998). For engineering design, this is a critical phenomenon, since the design of functional expansion requires new methods, coming and adding to the well-known methods of functional combination and optimization (Le Masson *et al*., 2017).

However: is this phenomenon so strong? Maybe it is just one type of products that is hit by this phenomenon, maybe functional expansion just happens once or twice on certain products and maybe functional combination and optimization still largely dominates the realm of product design? This would be the so-called "Lancasterian" hypothesis: Kelvin Lancaster is a very famous economists who, in the 60s, wondered how the general equilibrium model of economics, at that time based on the hypothesis of a finite (fixed) list of products, could be adapted to account for the phenomena of regular renewal of products that was already largely visible in the 60s, a time of mass-diversity and regular evolutions of mass consumption products. Lancaster saved the general equilibrium by proposing a theory (Lancaster 1991; Lancaster 1966) based on the hypothesis that product performances increase but each product has a stable set of function that defines it. Doing so he could rewrite the equations of general equilibrium on the set of (fixed) performances. This was a great success in economics. But this result is based on the hypothesis that there is no functional expansion. And to our knowledge, no studies were ever launched to check this hypothesis. By contrast, for some authors, this phenomena of "functional expansion" is a unique and specific feature to characterize contemporary innovation (Le Masson *et al*., 2010; Witt 2009; Becker *et al*., 2006); according to these authors, it is a phenomenon that is particularly visible on mobile phones but might also exist on other products; and it is a phenomenon that would have significantly increased in the last decades. Hence our research question: is the phenomena of functional expansion visible over long time period and on different products? And does this phenomenon increase significantly in the 1990s?

Testing these hypothesis raises critical issues: in case of functional optimization and combination engineering design can rely on several predictive models; when it comes to functional expansion, even basic elements are missing: 1) it is not self-evident to just roughly evaluate the phenomena of functional expansion. One can generally agree that the mobile phones changed to become "smarter" - but can one measure the level of functional expansion? Can one compare functional expansion on mobile phone with functional expansion on other products? 2) it is difficult to propose a reasonable predictive model because we don't know what might be relevant predictive variables. We need to relate the process of functional expansion to specific engineering resources and build a simple predictive model that would account for functional expansion, ie we need a so-called "law of expansion". If one would have a measure of functional expansion and this law of expansion, then it could become possible to test whether functional expansion significantly evolved in the last two decades.

Hence the program of this paper is as follows: building on existing literature, we will propose a way to measure functional expansion; building on recent advances in design theory, we will be able to propose a law of expansion; applying the law of expansion to our data of functional expansion, we will test whether there was a significant increase in functional expansion in the last decades.

2 LITERATURE REVIEW AND RESARCH QUESTION: FUNCTIONAL EXPANSION AND CHANGES IN DESIGN REGIMES

2.1 Measuring functional expansion

Over time, research on innovation analysed specific types of innovation. In early 20th century, innovation was associated to productivity, and political economists measured the productivity in steel industry or in coal mining. In mid-twentieth century, one rather measured the diffusion of innovation with equipment rates; one also measured functional performance increase (decrease in fuel consumption, increase in safety, comfort,…). Since contemporary innovation seems to consist also in functional expansion, we need to develop a new instrument. Note that this instrument was actually suggested by a Kelvin Lancaster himself, who explained how his hypothesis should be tested (Lancaster 1991; Lancaster 1966). Building on Lancaster, the requirements for the measurement are as follows (and are quite demanding):

a) requirement 1: one measures "functions" in the sense of "reason to buy" - so many 'technical functions' should be ignored as long as they are not 'existence conditions' for a product on a market. Lancaster call them "product characteristics that have an economic effect". These are the "purchase" criteria that a buyer should you to maximise his/her utility function.

b) requirement 2: since it is difficult to access to all products of a certain family on a given market (all mobile phones on the French market at time t1), there is a sampling issue: how to sample all the products of a certain family on a certain market at time t1; and the sampling process must be stable over time.

c) requirement 3: the method has to be stable over time; there are two apparently conflicting requirements here: one has to avoid "anachronism" effects in which an observer of time t2 judges the emergence of function at time t1, t1<<t2; and this calls for "synchronous" observers (observation of functional changes at time t1 is made by an observer present at time t1); but one has to avoid too strong "subjective" differences so observers at time t1 and t2 have to share common criteria to evaluate the functional emergence.

One solution suggested by Lancaster is to rely on consumer reports. One can explain this suggestion:

a) consumer reports are "utilitarian" by construction: they claim to only focus on "pure" functions, avoiding fashions or so called "technical functions" that only technical experts could understand and value. Hence it meets requirements 1. Note that they will tend to "underestimate" functional expansion since they ignore some functions that might be a "function" for a few buyers. Note also that they are supposed to be independent from product designers.

b) consumer reports are companies or association that build on all the marketing knowledge for a given family of product on a given market for a given period of time. Hence they have developed a sampling capacity. Note that, as independent prescribers, they are supposed to control for possible biases (brand or company biases) in the sample. Hence they meet requirement 2.

c) consumer reports are companies and association that are stable over time: they make regular evaluation over time, hence there is a "synchronous" measurement; and they have well-established rules that are kept stable over time to evaluate what is a function - hence this is a synchronous and yet objective measurement instrument. Hence they meet requirement 3.

Recent works have helped to develop a new method for measuring functional expansion at an industry level based on consumer reports (El Qaoumi *et al*., 2017). These works have already largely validated the method. The measurements made on 4 types of products led to prove in particular that Lancaster was wrong. In this paper we built on the same method, relying on a larger set of products (we increase the data base to 8 families of products).

2.2 A model of functional expansion

What are the available models to account for functional expansion and functional combination? It is well-known that the existence of a new product will depend on customer acceptance (in a 'demand side' perspective) or technical discoveries (in a 'supply side' perspective). These approaches (detailed for instance in (Arthur 2009; Saviotti 2001; Saviotti and Metcalfe 1991; Nelson and Consoli 2010)) have taught us that a new product will require knowledge creation, either from the science point of view (knowledge creation for making discoveries and designing a new technique) or from the market point of view (knowledge creation to design new usages of the new product). *Hence a model of functional expansion should depend on the overall effort put on designing (the techniques and/or the usages)*. Hence the *design effort* is a first dimension that should characterize a design regime. Some authors went as far as considering that this single should be enough and propose, for instance, a Poisson law for the emergence of new products or new techniques where the Poisson parameter is proportional to R&D investment (see (Aghion and Howitt 1992), an endogenous growth model). But this model was considered as too simple and not empirically confirmed (Jones 1995).

A critical limit of a Poissonian model is that it considers that the events are independent - whereas many works have underlined that existing techniques might have more or less generic effect, ie enable more or fewer combinatorial applications, depending on the set of already existing technologies, the knowledge heritage. This logic of higher or lower generativity is illustrated by the works of Fink *et al.* (Fink *et al*., 2017) showing that in situations of "combinative" innovation, some new building blocks can have a much higher generative power than other (Fink *et al* paper relies on three combinative situations where a new 'component' enable a certain number of new 'products': how a new letter added to a given list of letters enables to create new words; how a new ingredient added to a list of ingredients enables to create new recipes; how a new software development tools added to a list of software development tools enables to create new software). This model corresponds to so-called "generic"techniques (Kokshagina 2014; Bresnahan and Trajtenberg 1995) that can have an impact on several markets and applications, hence having much higher "generativity" power than a non-generic one. Hence the model of functional expansion should integrate the issue of genericity of the newly created function. It means that there is an "heritage" that determines the potential of future functional expansion. This is not only a "path dependency" (David 198, in the sense that it does not only describe the limits and restrictions to expansion but describes also the potential of future expansions.

How can one model this "heritage" of techniques that would determine expansions? It is today well-known that the logic of lower and higher genericity depends on *the structures of techniques and the interdependencies between techniques*: in the so-called C-K/Ma model, (Le Masson *et al.*, 2016) model a system of techniques by the interdependences and is able to account for the expansion of systems of techniques. The paper also proposes a computable model that predicts the dynamics of a system of interdependent techniques. Hence C-K/Ma can lead to *propose a law of functional expansion parameterized by the design effort and taking into account the "heritage" of techniques that determine the potential of functional expansion*.

2.3 Research questions: characterizing design regimes and their evolutions

Based on the literature we have a measurement technique to measure functional expansion and we have building blocks to propose a law of functional expansion. In this paper we fit this law with the empirical data. *Our first research question is to check whether the law fits with the empirical data*.

Moreover, if there is a fit, this fit will reveal the design regime associated to the functional expansion. Hence it will be possible to test whether there is a significant change in the design regime over time. *Our second research question is hence to check that there is a change in the design regime - and check whether this change occurred in the mid 90s*.

We now build a law of function expansion in design regimes. We then present the empirical material and proceed to the tests.

3 A LAW OF EXPANSION IN DESIGN REGIMES

3.1 Principles of C-K/Ma

We build our law on the C-K/Ma model (exposed in (Le Masson *et al.*, 2016)). In this model, a technique is an element of a matroid. The structure of techniques is the matroid of techniques. A product is called a "working system", it is made of techniques that 'work together', techniques that can be said 'compatible', which correspond, in matroid terms, to a circuit. If we consider a graphic matroid G, the elements are edges; each technique is an edge ti, E = E(G) is the set of edges of the graph; a working system (a product) is a circuit and in a graph, a circuit is actually a path made of edges (techniques) that is connected and all vertices are of degree 2, ie the circuit foes only once through each vertex (see figure 1 below).

In this model, what is a function? It is both a property of a product and the effect of (at least) one function. In a graph, *one can assimilate a function to a vertex that is on a circuit*: a vertex on a circuit can be associated to two techniques and is an element of a product. The vertices of the graph are V(G). In (Le Masson *et al.*, 2016), the authors use the example figure 1 below: the graph G below can be interpreted as a synthesis of the technological know-how of a designer. The designer knows how to address {f1; f2; f3} (with the circuit t12-t23-t31); he doesn't know any solution to address {f1; f4}. A matroid can be associated to this graph of designer's knowledge, the matroid defined by the cycles of the graphs. In this matroid {t12; t13} is independent whereas {t12, t13, t23} is dependent. {t12, t45} is also independent.

The matroid representation has the first advantage to focus on the interdependencies inside a structure of techniques and to characterize all the known combinations that correspond to a product (all the cycles in the matroids). It also provides a critical 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(G) = |V(G)|-1. (r(G)=4 in the example below), where |V(G)| is the number of vertice.

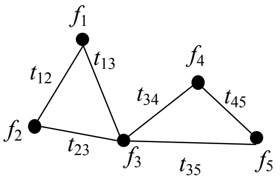
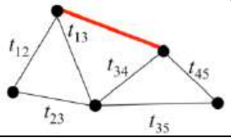
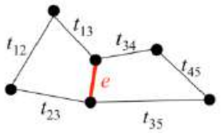


Figure 1: A graph G

C-K/Ma models the design of a new matroid from a given one. The paper shows that the design of a new system of techniques actually relies on two main operations (see table below):

- The extension, that consists in drawing a (dependent) edge between two existing functions to create a new circuit. This operation corresponds to a new product (working system) that is exactly the new combination of known functions. The impact of the extension on the structure of techniques is as follows: it doesn't change the rank r of the matroid; it decreases (by minus 1) the number of remaining possible combinations not done yet. Hence it decreases the potential of functional combination associated to the known techniques. Note that an extension is not possible if the matroid is said complete: this corresponds, in a graphic matroid, to the situation where there is an edge between any pair of vertices.
- The co-extension, that is less intuitive, and corresponds to a new independent edge common to several connected components. This operation corresponds to designing a generic technique, generic to several technical families. It adds one new function - this operation is the unique operation that enables functional expansion. In matroid terms, a co-extension corresponds to an extension made on the dual of the matroid. The impact of the co-extension on the structure of techniques is as follows: it increases the rank r of the matroid (by +1) ; it increases (by r) the number of remaining possible combinations not done yet. Note that, surprisingly enough, a co-extension is not possible if the dual of the matroid is complete.

Table 1. Main design operations in the dynamics of technique and in matroid (last colomn: illustration on the graph G of figure 1)

Cumulative design of working systems with new technique linking other techniques and minimizing propagations	*Extension* ie one dependent edge, depending on the techniques to be linked together	
Designing a generic technique, generic to several technical families	*Coextension* ie one independent edge common to several connected components	

3.2 Relying on C-K/Ma to build a law of expansion in design regimes

Let's now begin to model a design regime: given a certain product type T, we associate to T the set of techniques that enable to design the existing products. Techniques used in a known product are said dependent. The techniques are defined so as to meet the axioms of matroid (in (Le Masson *et al.*, 2016), the authors explain how to describe a structure of technique to meet the axioms of matroid theory). We suppose that the resulting matroid is graphic. To each edge of the matroid, we associate a function. This defines the initial rank, r0, of the matroid M of techniques of T.

We now design a new technique. Unless the matroid is complete, an extension is possible. Unless the dual is complete, a co-extension is possible. These operations can be repeated. In the repetition, a constraint emerges: extensions or coextensions, enabled alone, lead to deadlocked systems since extension leads to complete the matroid and co-extension leads to complete its dual. Hence a direct consequence demonstrated in (Le Masson *et al.*, 2016): "*the only way to get an unlocked dynamic consists in combining extension and coextension – ie the combination of the design of working systems and the design of generic techniques*".

This key property enables to identify several design regimes, and two of them deserve particular attention: the 'extension-driven' and the 'co-extension' one.

1- The "*extension-driven" regime* gives priority to extension (the design of working systems). In this regime, co-extensions (the design of generic techniques) are as rare as possible. Over time the matroid becomes complete and no extension is possible anymore. Hence one co-extension is required, it increases the rank by +1 (the rank becomes r0+1) and the generativity by +r0. Over time the rank increases slowly: one co-extension that increases the generativity by r0 and the rank with +1, then r0+1 extensions until generativity decreases to 0 and again co-extension, this time with the rank r0+1, then r0+2 extensions, etc. *In this regime, the creation of generic technique is "endogenous",* in the sense that the internal logic of the extension of techniques pushes to 'invent' a new technique that changes the game. This contrasts with a logic where co-extension appears without the internal 'pressure' of extension (see below). Note that this can describe regimes with "low" functional generation or "high" functional generation" - this will mainly depend on the intensity of the design effort (see Next and Ncoext in equations 1 and 2 below).

In this regime, one can write the law of extension: at time t, the rank is r(t), at time 0 it is r0. At time 0, r0 extensions are possible. At time r0+1 a co-extension is required and the rank becomes r0+1. And so on. Hence at time (r0+1) + (r0+2)+…. + (r0+k) the rank is r0+k (see Figure 2 below).

Hence the equation:

$$r\left(k.r_0+\frac{k.(k+1)}{2}\right)=r_0+k$$

Hence $r(t)=r_0+k(t)$ with $t=\frac{k^2}{2}+\left(r_0+\frac{1}{2}\right).k$. There is one positive root for this equation:

$k=\sqrt{(r_0+1/2)^2+2t}-(r_0+1/2)$. Hence the general equation:

$$r(t)-r_0=\sqrt{(r_0+1/2)^2+2t}-(r_0+1/2).$$

If there is N_{ext} new techniques created per unit of time in this regime, then the equation becomes:

$$r(t)-r_0=\sqrt{(r_0+1/2)^2+2N_{ext}t}-(r_0+1/2).$$

If $N_{ext}t \ll \frac{r_0^2}{2}$, then $r(t)-r_0 \approx \frac{N_{ext}t}{\left(r_0+\frac{1}{2}\right)}$; If $N_{ext}t \gg \frac{r_0^2}{2}$, then $r(t)-r_0 \approx \sqrt{2N_{ext}t}$ (see figure 2).

Note that this law supposes that the matroid is fully completed. We could have a variant with a "saturation" at level rmin or at a fraction β of the full completion. In the first case: this consists in replacing r0 with r0-rmin. In the second case the fraction β shortens the time to reach completion, hence:

$$r(t)-r_0=\sqrt{(r_0-r_{min}+1/2)^2+2\mathrm{N}_{ext}\beta t}-(r_0-r_{min}+1/2). \tag{1}$$

Or: $(r(t)-r_{min}-1/2)^2-(r_0-r_{min}-1/2)^2=2\mathrm{N}_{ext}\beta t$, linear in t. (1')

2- Conversely, the "co-extension-driven" regime favors co-extensions. We have then a symmetrical situation: a hand of dependent systems and many independent techniques. In that case the invention of a generic technique is not driven by the internal constraint of the system of techniques. Hence this is an *exogenous creation of independent techniques*. Note that over time, an extension becomes necessary to make an additional co-extension. This constraint implies a law on the "co-extension driven" regime: we have the following relation:

$$r\left(k.r_0^*+\frac{k.(k+1)}{2}\right)=r_0+k.r_0^*+\frac{k.(k+1)}{2}$$ where r* is the rank of the dual of the matroid.

Hence $r(t)-r_0=t-k(t)$ with $t=\frac{k^2}{2}+\left(r_0^*+\frac{1}{2}\right).k$.

Hence we have:

$$r(t)-r_0=t-\left[\sqrt{(r_0^*+1/2)^2+2t}-(r_0^*+1/2)\right].$$

If there is N_{coext} new techniques created per unit of time in this regime, then the equation becomes:

$$r(t)-r_0=t-\left[\sqrt{(r_0^*+1/2)^2+2N_{coext}t}-(r_0^*+1/2)\right]. \tag{2}$$

If $N_{coext}t \ll \frac{r_0^{*2}}{2}$, then $r(t)-r_0 \approx N_{coext}t$; If $N_{coext}t \gg \frac{r_0^{*2}}{2}$, then $r(t)-r_0 \approx \mathrm{t}-\sqrt{2N_{coext}t}$ (see figure 2).

Note that, contrary to what appears on figure 2, r_0^{*2} is usually relatively big: in a matroid M we have $r^*+r=|M|$ where $|M|$ is the number of elements in the matroid (ie edges for a graphic matroid) -

when M is complete the magnitude of $|M|$ is in the order of r_0^2 so the order of magnitude of r_0^{*2} is r_0^4. Hence a very steep slope for the exogenous curve below.

3.3 Conclusion: a law to characterize functional expansion

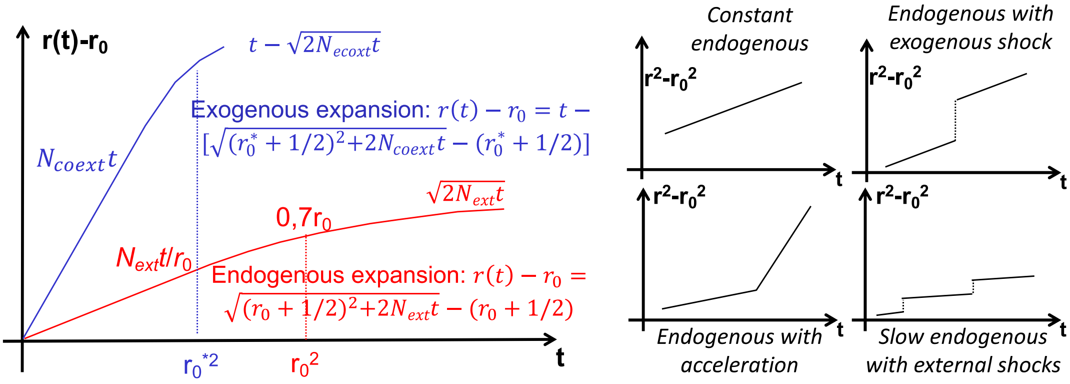


Figure 2: models of functional expansion (left graph: "pure" exogenous (blue) and "pure" endogenous cases (red); right: four mixt cases, represented on the anamorphosized data).

In the model above (eq. 1'), *a design regime can be characterized as a base of endogenous expansion with occasional exogenous expansion*. An endogenous expansion is characterized as a straight line in the graph $(r(t) - r_{min} - 1/2)^2 - (r_0 - r_{min} - 1/2)^2$ vs t, and its slope $2N_{ext}\beta$ relates to the design effort. A very low slope relates to an almost *pure functional combination (almost no expansion)*. A positive break in the slope indicates an *intensification of the design effort* (change in the design regime). The endogenous regime can punctually be enriched by non-endogenous expansions. This creates a jump, *a break in the curve with a constant slope* (see figure 2).

4 TESTING THE LAW ON EMPIRICAL DATA

4.1 Material: empirical data on functional expansion

We used the archives of the French Consumer Report Que Choisir. We followed 8 types of products (see below) and we had access to integral archives of each product study of the period below.

Table 2. Sample: 8 consumer products, time period and number of studies during the period

Type of product	Period	Number of studies
Iron	1962-2014	24
Vacuum Cleaner	1969-2014	37
Freezer	1970-2014	17
Refrigerator	1973-2014	21
Toothbrush	1975-2014	7
Bicycle	1975-2014	13
Mobile phone	1996-2014	24
GPS	2007-2014	10

For each product, we compare the functions in the new test at time t+1 with all the functions that appeared in the test between time 0 and time t. If the function is semantically (significantly) different we consider it as new. We had a double (in certain cases triple) coding. We represent the result on the graph below (aggregated new functions until the date of the study vs date of the study, figure 3).
This graph calls for some comments:

- There is, for the 8 products, a visible functional expansion. Even the toothbrush shows regular creation of functions. The slowest functional expansion is the refrigerator.
- The fastest expansion is the smart phone - this is coherent with the intuition we mentioned in our introduction. It created 113 new functions in 18 years. Less intuitive is the fact that the vacuum cleaner created more functions (124) than the mobile phone, even if on a longer time period (46 years).

- This tends to invalidate Lancasterian hypothesis: there is a functional expansion on many products, not only on smart phones. We need to test it.
- Regarding our second hypothesis: it is less self evident that there is a regime change in the 90s even if it seems that there is a break in the design of vaccum cleaner around 1992, a break for Iron around 1995, a break for bike around 1995. This also needs to be tested.

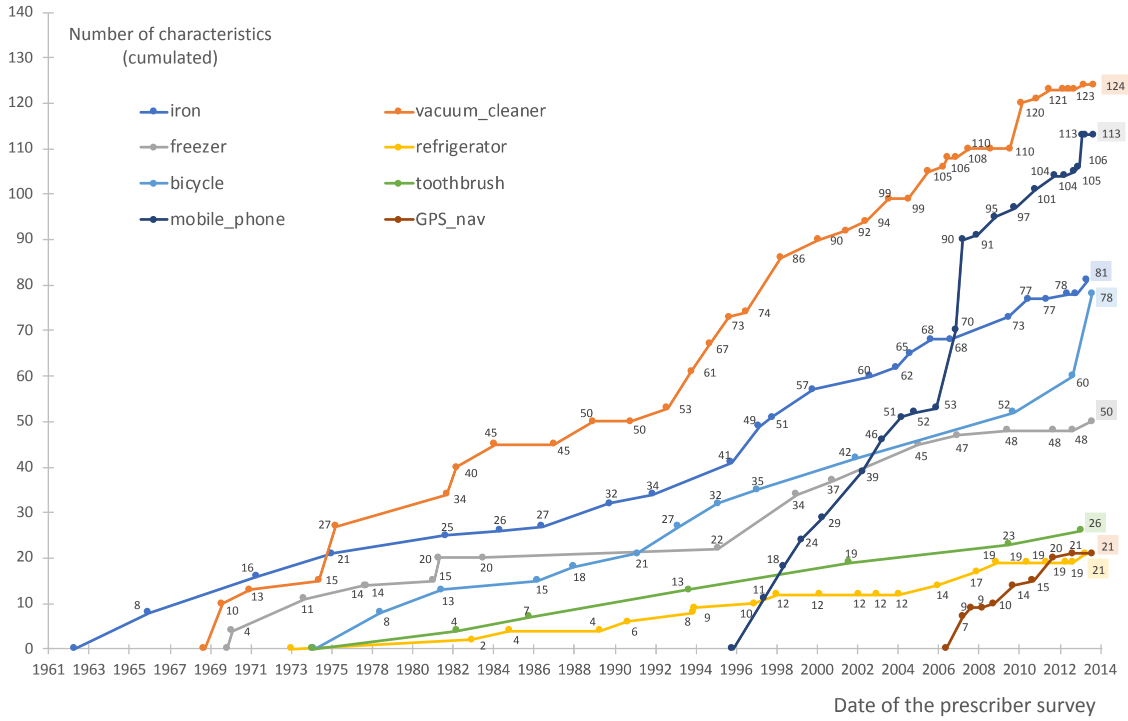


Figure 3: Empirical measurement of functional expansion on 8 consumer goods (w axis: time; y-axis: cumulated number of characteristics). Ex: in 1971, after the third study on vacuum-cleaner, the product vacuum-cleaner has gained 13 additional functions since the first study (done in 1968)

4.2 Result: fit of the law of functional expansion and change in functional expansion.

We fit the graphs of measurement vs time with the law of endogenous expansion. For the reader, we represent below the anamorphosized data (on y axis: $(r(t)-1/2)^2-(r_0-1/2)^2)$ (figure 4).

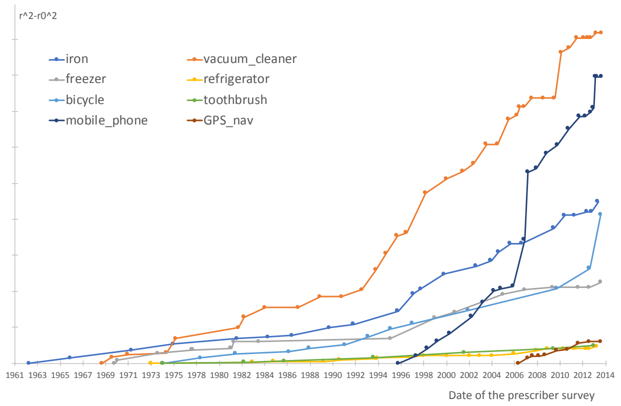


Figure 4: $(r^2-r_0^2)$ *vs time: the breaks of slope and the jumps in the curves are more visible*

For each product, we fit the endogenous expansion model (eq. 1') and estimate the slope as follows: for each product we conduct a regression on the all period, then we conduct a Chow test on all possible break dates to identify possible significant breaks in the regime. For each significant break we characterize the two regressions (before and after the break) and we check whether the slopes are significantly different (confidence interval at 95% level). In that second case, it means that the break in linear regression is a jump. The results are summarized in table 3 and below:

- Four products follow a model of endogenous expansion with a significant slope break: iron, vacuum cleaner, freezer and bicycle (the latter without outlier 2014). In a first phase there is slow endogenous expansion then a stronger one. The slopes ratios and dates are: 2,6 (freezer, in 1995-1999), 3,3 (bicycle; in 1991-1993), 3,66 (vacuum cleaner in 1993-1994) and 4,47 (iron in 1992-1996).
- One product follows a strong endogenous expansion with a jump: the mobile phone. The slope is very high (between 565 and 786). There is strong jump (in 2006-2008), without significant change in slope. It corresponds to the first "smart phones", that implied a strong change in the technologies (Glimstedt 2018).
- Two products follow a constant endogenous expansion: toothbrush and GPS. The toothbrush has one of the lowest slope (28,7); the GPS is relatively high (around 151).
- One product follows a very slow endogenous expansion: the refrigerator (slope around 25, with long periods of no changes in the functions, which explains why the regression is less significant). There is at least one testable jump (around 2006-2008; no significant change in slope) which can be considered as an exogenous expansion in a very slow endogenous expansion. This corresponds to the (well-known) fact that innovation on this product is largely driven (and constrained) by energy consumption, hence the very limited functional expansion.
- Additionally, one can notice other jumps on some curves: a jump in 2011 on vacuum cleaner (robot vacuum cleaner), a jump in 2014 on bicycle (electric bike). There is a (light) jump in 2014 in mobile phone related to a strong enrichment of camera functions.

Table 3. Results

	a	t_stat	Chow	p-value	a-before	p-value	conf int 95%	a-after	p-value	conf int 95%	Slope break
iron	197,99	***	1992-1996	2.10-14	68,2	***	[58; 78]	305	***	[284; 326]	yes
vacuum cleaner	461,41	***	1993-1994	2.10-16	176	***	[150; 201]	644	***	[610; 677]	yes
freezer	100,8	***	1995-1999	0,001	46,9	**	[22; 71]	121,9	***	[80; 164]	yes
bicycle (2014 outlier)	140	***	1991-1993	0,001	53	**	[33; 73]	175	***	[141; 209]	yes
mobile phone	1015,8	***	2006-2008	3.10-9	565	***	[439; 691]	786	***	[620; 951]	no
GPS	151,7	***	no								
toothbrush	28,7	***	no								
refrigerator	27,7	***	2006-2008	6.10-5	20	***	[17; 23]	26,9	*	[1; 52]	no

With these results, we can conclude on our research questions:

- Research question 1: a regime of functional expansion is present in all products. - at a very low pace for refrigerator or toothbrush; at a surprisingly high pace for vacuum cleaner or iron. And, as expected, at the highest pace for mobile phone. This means that even if irons or vacuum cleaners seem to remain "the same" over time, the reasons to buy them have significantly changed for the last decades.
- Research question 2: for the 6 products with long life time, 4 on 6 show a significant change in slope and this change in slope occurs in the 1990s (the earliest: bicycle 1991-1993, then vacuum cleaner 1993-1994, then iron 1992-1996, and finally freezer 1995-1999). The refrigerator and the toothbrush don't show a significant change in slope.

5 CONTRIBUTION AND DISCUSSION: 'DESIGN-METRICS' AND DESIGN HERITAGE

To conclude: this paper shows that *it is possible to predict a law of functional expansion of products and this law was successfully tested on a sample of 8 consumer products*. Contributions are as follows:

- We prove that functional expansion is not limited to mobile phone - it exists for all the tested consumer products.
- We prove that functional expansion significantly accelerated in 1990s.

Confirming the intuition of functional expansion, this work suggests that we are in a non-Lancasterian economy, an economy of functional expansion, hence it underlines the need to prepare the designers (engineering design as well as industrial design or architectural design) to functional expansion and not only to optimization. This is also important for managers of innovation management.

Moreover this work is a first step towards a "*design-metrics*"*:* we have relatively few methods to measure innovation; and we have even less when it comes to measure expansion. It is already quite difficult to measure an "increase" (or decrease) of a functional performance; we can't underestimate the difficulties to measure the emergence of new dimensions. This work paves the way to further research on measuring expansion of products. We have today many techniques of measurement in "econometrics" - but these techniques focus on optimization into a stable frame of references - they ignore generativity. If the expansion becomes critical for competition, we need today new methods and tools to measure and predict it. This calls for the development of a 'design-metrics', a discipline that would try to measure contemporary phenomena of design generativity, that are largely ignored by "econometrics" and could become critical for our societies.

Finally, this work also leads to a critical theoretical result: the empirical data confirm a model of "endogenous functional expansion" and this means that functional expansion, that is deeply related to "disruptive" innovation, actually relies on an *"heritage" of previously designed techniques* that actually determines the potential of future expansions. This heritage is more than a "path dependency" in the sense that it does not "reduce" the possibilities but it actually 'creates' them. And this heritage can be characterized by the interdependence structure of its elements. This result doesn't exclude exogenous shock but it reminds that endogenous logics can be very powerful and can explain contemporary logic of functional expansion.

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Designing Decisions in the Unknown: A Generative Model

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This study examines how design theory enables to extend decision-making logic to the 'unknown,' which often appears as the strange territory beyond the rationality of the decision-maker. We contribute to the foundations of management by making the unknown an actionable notion for the decision-maker. To this end, we build on the pioneering works in 'managing in the unknown' and on design theory to systematically characterize rational forms of action in the unknown. We show that action consists of designing decisions in the unknown and can be organized on the basis of the notion of a 'decision-driven design path,' which is not yet a decision but helps to organize the generation of a better decision-making situation. Our decision-design model allows us to identify four archetypes of decision-driven design paths. They enable us to discuss the variety of known organizational forms that managers can rely on to explore the unknown.

Additional supporting information may be found in the online version of this article at the publisher's website.

Keywords: unknown; design theory; decision theory; generativity

Introduction

In a paper recently publish in *Science* (Bonnefon *et al*., 2016), the authors study how an algorithm should 'decide' when confronted with a question such as 'If the brakes have failed, should the driver system of the car kill the pedestrians crossing the street or save the pedestrians by crashing the car into a wall, thereby killing the occupants of the car?' One can immediately understand the dilemma, and can be tempted to find an alternative option that is unknown to date, but would definitely surpass the two options presented.

This example underlines a basic issue in management science: rational choice is often taken as a given, but there are sometimes 'unknowns' that are beyond rational choice and could deeply influence the rational choice. Hence, the general question is can one extend decision-making to the unknown to rationally support the creation of options?

This issue has largely been addressed by research in strategic management and risk management (Wideman, 1992; McGrath and MacMillan, 1995, 2009; Pich *et al*., 2002; Cunha *et al*., 2006; Loch *et al*., 2006, 2008; Mullins, 2007; Weick and Sutcliffe, 2007; Sommer *et al*., 2008; Rerup, 2009; Feduzi and Runde, 2014; Feduzi *et al*., 2016). The issue of the 'unknown' is famous both in professional circles (Wideman, 1992) and in the work of decision-theory scholars (Miller, 2008). Studies have contributed to clarifying what is 'unknown' in relation to decision-making: decision-makers are confronted with 'the unknown' when they are *confronted with alternatives and events that were not imagined and taken into account before and still might impact them to a considerable extent by radically changing their decision situation*. More formally and more precisely, it has been shown that 'the unknown' corresponds to a type of situation that cannot be handled by the theory of decision-making (Loch *et al*., 2006). The issue is *not* related to decision bias (a phenomenon that has largely been investigated), but to generation bias (a phenomenon that is, formally speaking, not included in decision theory).

As will be shown in the literature review, studies have described and addressed the challenge of managing the unknown: they have contributed to clarifying the goal of generating an improved decision situation and meeting the challenge of overcoming generation bias by presenting multiple ways to generate specific alternatives. However, they have failed to develop a systematic approach to the unknown and a structured map of the paths in the unknown that could contribute to improving the decision situation. Without such a formal framework, they tend to return, more or

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less implicitly, to 'decision-making in conditions of uncertainty.' Typical examples can be found in (Sommer and Loch, 2004; Loch *et al*., 2008): in these papers, the authors explain that the issue stems from the fact that, in a decision situation, the actors cannot know all of the possible alternatives and states of the world, and explain that managing in the unknown consists of *discovering or generating* new alternatives and new states of the world. However, in the following paragraphs of the papers, the model they use is actually a *restriction* of an *ideal* set of alternatives and events, which is no longer a model of extension, but rather a model of *restriction*, which is well-known in decision theory. This restrictive approach precludes an analysis of all facets of the *generation* of alternatives and states of the world.

Hence, the aim of this study is to follow the program outlined by Loch *et al*. (2006, (2006, 2008) and (Feduzi and Runde, 2014) to develop normative models that can provide 'the standards for comparison and evaluation that are fundamental to the progress of both descriptive and prescriptive work' (Feduzi and Runde, 2014: 269). We are seeking *a model for the generation of new states of the world and new decision alternatives*. That is, we propose a formal model of the *extension of decision-making theory to the unknown*, or simply a model of 'decision design' in the unknown. The requirements for such a model can be listed: this extension should be formally consistent, it should contain the decision logic, it should help characterize and understand critical phenomena that occur when actors are confronted by the unknown, and it should lead to a discussion of a new organizational logic related to the unknown, making sense of the multiple forms and notions that have been identified in contemporary management of innovation and could actually be related to different types of 'management in the unknown.'

As will be described in the literature review, one of the key issues in such a research program is to develop a *model of generativity that is adapted to decision-making*. This is possible because of the great advances in recent years in the field of innovation management, wherein researchers must analyze situations where collective actions, organizations, and strategies consist of addressing the issue of previously unknown products, services, business models, and competences. Hence, the findings of recent studies on innovation management, and more precisely those on design theory for innovation management provide us with a model of generativity. Can it be applied to decision-making? In this study, we show how models of generativity developed for innovation management can actually be used for *decision design in the unknown*, that is, the generation of 'better' decision-making situations, and thus can enrich the field of decision-making in the unknown.

This paper follows a classical construction: literature review, methodological approach, construction of the model, results of the model, and discussion. Hence in the next part, our literature review identifies a twofold gap that should be bridged by a formal model extending decision theory to the unknown: (1) the model should formally (systematically) account for the various ways of 'broadening' a decision space; and (2) the model should help characterize the performance of this process in terms of 'comprehensiveness' (Feduzi *et al*., 2016) and 'offsetting cognitive biases' (Feduzi and Runde, 2014). As we will show, while decision theory helped characterize 'selection bias,' our model should help characterize 'generation bias.' In the third part, we present our method and, in particular, explain why it appears fruitful to rely on design theory to model the extension of the decision-making framework to the unknown. Research has enabled the development of a basic science, design theory, that accounts for the unique phenomenon of design, namely generativity, and is comparable in its rigor, foundations, and potential impact to decision theory, optimization, and game theory (Hatchuel *et al*., 2018). As a consequence, today, design theory appears to provide a promising way to model the generation of a better decision space from a given one. In the fourth part, we construct a formal model that extends decision theory to the unknown and present its main implications. In the fifth section, we present the results, i.e. we show how this model bridges our twofold gap. In the final section we discuss the results and present our conclusions.

Literature review

The unknown as a limitation to classic decision theory

As noted in (Buchanan and O'Connell, 2006), the history of decision-making could be considered to begin with prehistory. However, it was only after World War II that models of decision-making were progressively formalized and integrated into a general framework. Recent historians' studies have enabled us to understand the 'rational choice' movement that unfolded at the end of World War II and during the Cold War (Erickson *et al*., 2013).

One of the greatest achievements was the formulation of a general theory of statistical decision-making under uncertainty, first by Wald (1939, 1950a, 1950b), which was then extended to the so-called subjective expected utility theory (SEUT) by Savage (1951, 1972), and also codified in management science by Raïffa and Schlaifer (1961) (see in particular the in-depth analysis of 'how homo economicus became Bayesian decision-maker' in Giocoli, 2013).

According to this model, the decision-maker has to choose one alternative from among a set of available alternatives (actions) and each alternative will have certain consequences depending on which of the possible 'states of the world' occurs. These consequences have a certain 'cost' (or utility), and the decision-maker is able to assign a (subjective) degree of probability to each state of the world. In this condition, the theory predicts that there is a choice that optimizes the expected utility (i.e. minimizes the expected costs).

These studies propose a formal decision model that takes into account a certain type of 'unknownness,' namely, one that can be codified in probability terms. Economists have long been aware of the possibility of 'unknowledge,' or 'unknownness,' or uncertainty (Keynes, 1921/1973, 1937; Knight, 1921; Shackle, 1949, 1979, 1983). Uncertain events and uncertain consequences of choices were considered to be unknowns, but statistical decision theory under uncertainty integrates many of these 'unknowns'. This theory contributes to taming a certain type of unknown, namely, the type that can be reduced to uncertainty, that is, to subjective probability. This progress is illustrated by a series of papers published in the 1990s on the notion of 'unknowledge' in economics and in Shackle's work (Frowen, 1990b): the contributors show that certain types of 'unknowledge' identified by Shackle (Frowen, 1990a; Lachman, 1990; Loasby, 1990) can be integrated into decision theory (Hey, 1990). However, these works also show that one critical type remains: the 'residual hypothesis,' namely, the 'potential surprise,' the event that cannot be formulated and taken into account in the various states of the world. This is one type of unknown that is beyond the bounds of decision theory under uncertainty.

Challenging the unknown as a research issue in decision-making

One consequence of formal statistical decision theory under uncertainty is the capacity to draw a line between uncertainty, which is manageable using decision theory, and the unknown, seen as the 'new frontier' to be explored by decision-making theory builders. The problem of the unknown (or unknown unknowns (unk-unks) or black swan events) has attracted considerable attention in the management literature in recent decades (Wideman, 1992; McGrath and MacMillan, 1995, 2009; Pich *et al*., 2002; Cunha *et al*., 2006; Loch *et al*., 2006, 2008; Mullins, 2007; Weick and Sutcliffe, 2007; Sommer *et al*., 2008; Rerup, 2009; Feduzi and Runde, 2014; Feduzi *et al*., 2016). Of course, there are various understandings of exactly what unk-unks are, as explained by (Feduzi and Runde, 2014): authors can speak of 'events' or 'states,' and the term unk-unk 'extends variously to black swan events, unpredictable surprises, unimagined events, unexpected events, unforeseeable events, rare events' (Feduzi and Runde, 2014: 270). Following Feduzi and Runde (2014), we use a broad definition of the unknown that is relevant from the point of view of the decision-maker as modeled by statistical decision theory under uncertainty: (i) the decision-maker actually takes into account the states of the world, which are described with the minimum of detail that enables his/her to compute the cost associated with the consequence of his or her actions in the states of the world. Hence, when one speak of 'unk-unk' in relation to an 'isolated event' that has critical consequences, this implies, from a decision-theoretic perspective, that some *states of the world are unknown*; (ii) moreover, when the decision-maker uncovers unk-unks, he or she will also reconsider his or her initial set of actions. Further, the innovator or creative leader is described as being capable of imagining original, previously unknown courses of action (Nutt, 1993, 2000; Adner and Levinthal, 2004; Mintzberg and Waters, 1985). This implies, again from a decision-theoretic perspective, that *some actions are unknown*.

Hence, *from the decision-theorist perspective*, one can generally consider that the *unknown refers to all data relating to a decision-making problem that are not known by the decision-maker and that will impact the decision*. A decision-making problem can be 'broadened' or 'reframed' if one generates unknown states of the world or unknown alternatives that could change the decision. Thus, in this study, we address what we call the 'decision-challenging unknown': self-evidently, we are not interested in an unknown that would have no impact on the decision. The issue then is to identify the relevant unknown: can we know more about this decision-challenging unknown?

Early attempts to extend decision-making theory to account for the unknown

Very early on, the theory of statistical decision-making was the subject of multiple critics that opened the way to exploring an extension of the decision-making framework. From the Carnegie School of Business perspective (represented by Simon, 1947, 1955; March and Simon, 1958; Cyert and March, 1963, and more recently by Levinthal, 1997; Gavetti & Levinthal, 2000, 2004; and Gavetti *et al*., 2007), Simon (1955) describes the decision-maker as a 'satisficer' who cannot obtain *ex ante* all the detailed and well-structured information required by the theory of decision-making under uncertainty, and thus cannot act as predicted by the theory and so develops a search procedure that only leads to a 'satisficing' solution, rather than the optimal one. A second stream of work, involving the so-called behavioral decision theory, studied the nature of deviations that affect decision-makers (Edwards, 1954; Edwards, 1961; Tversky and Kahneman, 1974; Kahneman and Tversky, 1979; Bazerman and Moore, 2013).

Both streams of research studied facets of the process of hypothesis *construction and generation*. The studies in behavioral decision theory uncovered biases in the generation process: being attracted by too favorable hypotheses, we fail to generate alternative hypotheses, or we generate very similar ones (Fischhoff *et al*., 1977; Mynatt *et al*., 1993). The Simonian approach goes as far as working on models of thoughts describing discovery, addressing the issue of some forms of unknown beyond the known (Simon, 1977; Simon and Kulkarni, 1989), challenging Karl Popper's claim that 'there is no such thing as a logical method of having ideas or a logical reconstruction of this process' (Popper, 1959: 31–32; Simon, 1973).

In relation to generativity, the studies opened a new pathway to overcoming one of the critical limitations in decision-making theory: how to *construct* the 'residual hypothesis' (Shackle, 1983), that is, the list of alternate states of the world, and even the associated list of actions (Feduzi *et al*., 2016). Many of these studies were largely descriptive in nature, but also led to more prescriptive work aimed at developing techniques to assist the decision-maker to improve the quality of their decision-making. Some techniques are cognitive exercises that are recommended to enable the decision-maker to broaden the decision-making frame: 'consider the opposite' (Lord *et al*., 1984), or 'consider any plausible outcome for an event,' not just the opposite (Hirt and Markman, 1995), or take advantage of the variety of evaluation attributes when evaluating choices to screen alternatives and generate new ones (Miller, 2008; Larrick, 2012). Derived from Wason's (1960) discovery task, some methods systematize a process of alternative generation, either by disconfirmation (or eliminative induction, i.e., a Popper-style falsification; Popper, 1959; Farris and Revlin, 1989a, 1989b) or by counterfactual reasoning (Farris and Revlin, 1989a; Feduzi *et al*., 2016). Some methods are more organization-intensive, relying on a combination of alternative generation and knowledge acquisition. Hence (McGrath and MacMillan, 1995) examined the discovery-driven planning method, whereby decision-makers can discover alternatives and are told to keep a checklist to ensure that each assumption is flagged and tested as the process unfolds. Loch *et al*. studied complex learning processes involving parallel experimentation and selectionism (Loch *et al*., 2006), while Schoemaker (2008) proposed a method relying on forecasting and scenario planning.

Two key issues from a decision-making perspective

These studies identify two key issues that helped us to formulate our research questions:

1. *The design of a decision space as a new model of thought*. The studies characterize actors that not only decide, but also *design* the decision space. Of course, they *will* have to decide. Further, initially they are facing a decision-making problem, but instead of 'deciding,' they first engage in a 'generation' phase in which they switch from the initial problem to an extended one. Then, the issue becomes: how can one model this generation phase that transforms the initial decision space into a better one? The studies propose techniques to change the decision space, but there is no systematic approach to generativity. Hence, the first research question is: can one model the generation of a better decision space, i.e. can one model 'decision design in the unknown,' and, in particular, *how does a formal model of decision design help characterize the different directions of generativity?*
2. Rethinking performance criteria: *introducing comprehensiveness and generativity*. In examining the design of a better decision situation, the studies characterize what 'better' means. Two main ways to characterize the performance of the design process emerge. Some studies tend to increase the 'comprehensiveness' of the decision space, meaning 'the extent to which an organization attempts to be exhaustive or inclusive in making and integrating strategic decisions' (Fredrickson and Mitchell, 1984). Various empirical studies show a positive relationship between comprehensiveness and the performance of the firm (Eisenhardt, 1989; Priem *et al*., 1995; Miller, 2008). Another stream of studies considers that achieving full comprehensiveness of the decision space is less of an issue than resisting negative biases. These biases include 'functional fixedness,' 'satisficing,' 'selective perception,' 'concreteness,' 'anchoring,' 'availability,' 'confirmation bias,' 'predecisional distortion,' 'framing,' 'accessibility,' and 'focalism' (see Larrick, 2012: 461). More generally, we emphasize that this literature contributed to a great shift from the study of 'selection bias' (a classic focus in studies on decision-making) to 'generation bias' (for a synthesis, see (Cassotti, 2015)). Hence, there are criteria to evaluate how the generation phase led to improved decision quality. However, there is no systematic relationship between the techniques proposed in the studies and their performance. Hence, a second research question arises: *how does a formal model of the generation of a decision space increase comprehensiveness or defixation in the*

generation of alternatives, i.e. how does it help to deal with generation bias?

Learning from innovation management: extending the decision framework

To answer these questions, we rely on the results of recent studies on innovation management. The issue of the generation process has long been identified in innovation management studies. Innovation management has previously been influenced by decision theory, but also more recently by 'decision-challenging unknowns.' We summarize these two approaches below to show how they contribute to our twofold research question.

At the end of the, 19th century, Charles S. Peirce, who was working for the US Coast Survey, proposed to undertake research on the basis of the value of uncertainty reduction (Peirce, 1879; reproduced in, 1967 in *Operations Research*, 15, pp. 643-648). This risk-reduction approach was progressively extended to other innovation skills, for example, marketing was seen as a profession that was able to increase market knowledge to reduce market uncertainty. Some researchers went as far as applying option pricing methods based on the theory of decision under uncertainty developed in finance studies to the pricing of so-called 'real options' (Perlitz *et al*., 1999; Fredberg, 2007). The decision-making framework was also used for new product development and planning (see, for instance (Clark and Fujimoto, 1991; Thomke and Fujimoto, 2000; Kerzner, 2013), and for the economic evaluation of projects and project portfolios with market and technology uncertainty. Assimilating a new product development (NPD) project to an investment, it was possible to apply the tools and techniques developed for corporate investment to NPD projects: return on investment, net present value (NPV), and expected utility.

In recent decades, building on the studies on 'exploration' (March, 1991), another stream of research has analyzed the logic of generativity in innovation management. The authors of these studies have proposed organizational models to enhance exploration capacity in a systematic way, using either a 'modular' process model (Sanchez and Mahoney, 1996; MacCormack *et al*., 2001), wherein exploration and creativity can occur at the level of 'modular components' that are loosely coupled to the platform (Gawer, 2009), or a 'concept shift' process model (Seidel, 2007), whereby designers can explore a product concept not only in the fuzzy front-end phases but also later in the process, achieving a concept shift by modifying the concept's components. Numerous studies on radical and disruptive innovation have enabled researchers to characterize, analyze, describe, and prescribe the generative processes that help to deal with the unknown in a large variety of situations. They have proposed new criteria for evaluating the generation phases (see, for instance, Elmquist and Le Masson, 2009), and a large variety of new processes to deal with the unknown: new types of project management (Lenfle, 2016), new forms of competence management and value management (Hooge and Dalmasso, 2015), new ways to interact with the firm's environment through open innovation (Chesbrough, 2003) and open innovation in the unknown (Agogué *et al*., 2017), new ways to acquire knowledge through absorptive capacity (Cohen and Levinthal, 1990; Lane *et al*., 2006) and absorptive capacity in the unknown (Le Masson *et al*., 2012a; Kokshagina *et al*., 2017b), and new types of collaboration at the ecosystem level to face the unknown (Le Masson *et al*., 2012b; Lange *et al*., 2013).

As recently synthesized by (von Hippel and von Krogh, 2016), one of the critical issues addressed by studies on innovation management is related to the generation of 'need–solution pairs,' that is, finding creative solutions and discovering new needs. This corresponds to the generation of alternatives and various states of the world. However, these works focus mainly on the generation phase, which is also called the 'creativity' phase, and are only loosely connected with the decision-making issue. From an ambidexterity perspective, some authors even consider that they should be intentionally separated so that the decision criteria do not pollute the generation phase, that is, creating a generation bias by focusing too much on feasibility, marketability, and, more generally, existing dominant designs (Duncan, 1976; March, 1991; Tushman *et al*., 1997; Andriopoulos and Lewis, 2009; Birkinshaw and Gupta, 2013). From a more interactive ambidexterity perspective, some authors suggest that there should be some form of overlap and interaction. However, questions remain, because it is not always clear how the *initial* decision space stimulates the generation process. Many studies consider an initial generation phase that ends with an evaluation phase wherein a decision occurs. Maybe the generation phase could be better *driven* by the initial decision data, and would help overcome (and not cause!) the generation bias?

Research questions

Innovation management studies have enriched our knowledge, but have failed to resolve our twofold issue:

1. Modelling decision-making with generative options: can one model the generation of a better decision space, and in particular, how does this formal model help characterize the different directions of generativity, and does it help articulate creativity and decision-making? (RQ 1).
2. Designing performance-driven strategies consistent with the unknown: how does a formal model of the

generation of a decision space increase comprehensiveness or defixation in the generation of alternatives, i.e. help decrease generation bias? (RQ 2).

Von Hippel and von Krogh (2016) suggest that we should rely on formal models of generativity, such as C-K design theory (C for Concept, K for Knowledge), to better characterize generation processes, performance, and organizational facets. We follow that path in the rest of this paper.

Research method: integrating a model of generativity into the design of new decision spaces.

As noted in the literature, there are many studies on techniques to improve decision-making situations. However, the research gap is to propose a formal model that can *systematically* characterize the different ways to improve a decision-making situation. Hence, this paper is largely formal. This formal model helps to address cognitive biases and organizational issues. One of the consequences of this is that the paper relies on some mathematical symbols and formulae that may discourage some readers. We have tried to overcome this issue by keeping the equations to a minimal level and having one red thread example that should be considered as a simplified illustration of the general case treated formally. The technical details are presented in the Appendices that are available upon request from the editor. Our modeling research can be described in three steps as follows.

Step 1: from decision-making to the generation of decision spaces.

The general method followed by the Carnegie School and some of the strategic decision-making literature uses the classical model of individual decision-making under uncertainty as a benchmark, and analyzes how the 'real' decision-maker (or a behavioral model of the decision-maker) is often biased, and how some techniques might increase comprehensiveness or de-bias the decision-maker and help him or her to move closer to the 'ideal' situation (see Figure 1). This approach tends to underestimate the fact that, in this process, the so-called 'decision-maker' is actually *not* deciding, and the type of thought required from him or her during the process is *not* decision-making in the strict sense of decision theory. He or she is actually *generating* a new 'decision situation,' that is, the actor is actually following *generation reasoning*, and the generation is applied to a certain object that is not a new product (product innovation process) or a new service, business model, or idea (ideation process); it is applied to a decision space. In this study, we focus on this generation process.

Our method is as follows. We consider a given decision situation, apply a formal model of generativity, and analyze how this formal model modifies the decision problem (see Figure 1).

Applying this method raises two methodological issues: (1), what is our generative model? Below, we justify why we rely on C-K design theory; and (2), what is our model of a decision situation? Below, we justify why we select the Wald decision model as a model for the decision situation.

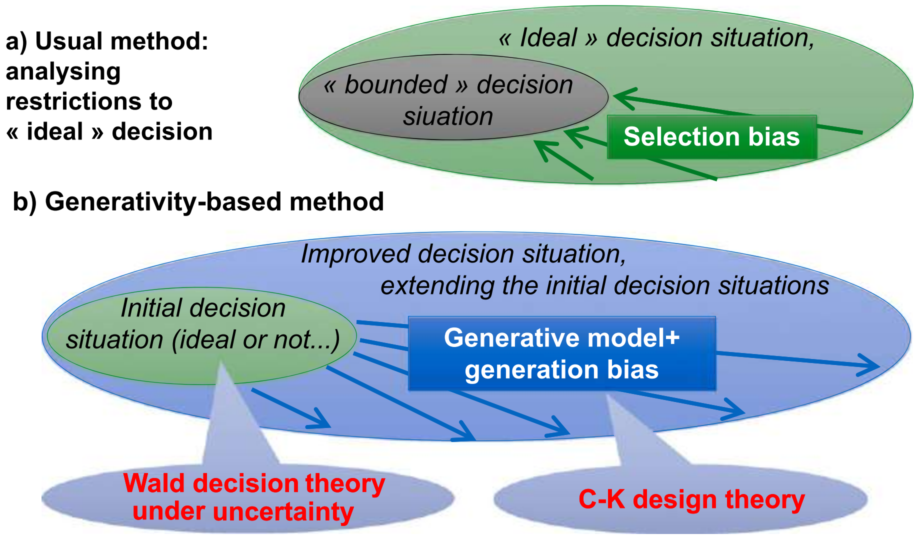

Figure 1 Method: from the study of selection bias to the study of decision-oriented generativity. [Colour figure can be viewed at wileyonlinelibrary.com]

Step 2: introducing a formal model of generativity: concept-knowledge (C-K) design theory.

Regarding the first issue mentioned above, we rely on design theory. Research on design theory has contributed to the development of a basic science that accounts for the logic of generativity and is comparable, in terms of its structure, foundations, and impact, to decision theory, optimization, and game theory.

Today, design theory is a powerful academic field with several competing and complementary theoretical proposals, particularly the C-K design theory that we use in this study (Hatchuel and Weil, 2009). Some critical properties of design theory, in particular C-K design theory, are of particular interest in relation to our research questions.

Design theory considers a variety of forms of *generativity*. Formal models of design theory such as general design theory (Yoshikawa, 1981; Tomiyama and Yoshikawa, 1986), axiomatic design (Suh *et al*., 1978; Suh, 1990), a coupled design process (Braha and Reich, 2003), infused design (Shai and Reich, 2004a, 2004b), and C-K design theory (Hatchuel and Weil, 2003, 2009) can all be characterized by their capacity to account for a form of generativity, as shown in (Hatchuel *et al*., 2011a). In particular, it has been shown that C-K design theory is more generative than Simonian approaches that aimed at modelling generativity but were 'unfinished' (Hatchuel, 2002). These theories have progressively evolved to become independent of professional languages and traditions. As a consequence, design theory appeals as a powerful integrative framework that can account for all activities involving generativity. In particular, studies have shown how design theory can account for generativity in engineering as well as in science (Hatchuel *et al*., 2013) and art (Le Masson *et al*., 2016a,b). *For our purposes, it appears that design theory is a model of generativity that is sufficiently general to be applicable to a decision problem.*

From a cognitive point of view, design cannot be reduced to a learning process or an experimental knowledge production process. Its departure points are the very powerful 'desirable unknown' or 'concept' (the 'C' in C-K design theory); that is, incomplete proposals that guide us towards the emergence of new values, uses, and identities of objects (e.g., products, services, processes, and business models) and new knowledge. Applied to a decision problem, it becomes possible to consider that, given a certain decision problem, a concept is the design of an improvement to the decision situation. The theory describes the process of *formulating and structuring this concept* and designing different ways to obtain better decision situations. *Hence, C-K design theory seems to be applicable to decision problems, and can help characterize, in the C-space, the variety of unknowns related to a decision problem.*

Concepts emerge from multiple heterogeneous knowledge (the 'K' in C-K design theory) resources, where K can be a decision problem. A design process uses C_0 and K_0 as inputs, and results in new concepts and knowledge at the end of the process, that is, new decision problems, as well as new unknowns. This means, in particular, that a design process creates knowledge. Hence, knowledge is both an input and an output of a design process. Thus, C-K theory helps to characterize the type of knowledge that must be gained in relation to certain types of unknowns. Hence, it also helps to characterize *the variety of processes that are required for exploration and knowledge creation to design new decisions*.

Last but not least, recent works on the cognition of creativity have enabled the characterization of fixation in design situations relying on the C-K design theory framework. Hence, C-K design theory serves as a reference for the generative process, and it is possible to characterize the biases associated with this reference (Hatchuel *et al*., 2011b; Agogué *et al*., 2014; Crilly, 2015). *Hence, we have the capacity to identify generation biases*.

As a consequence, C-K design theory appears as a formal model of generativity that can be applied to a decision situation as follows: K_0 is the decision situation to be improved, while C_0 can generally be written as 'design a better decision situation' (partially unknown). The design process will uncover the range of partially unknown decision situations that can be designed from the initial one (here we address research question 1). It is then possible to compare the newly created decision situations with the initial one and determine how much better they are. Fixation analysis, enables us to see not only the increase in comprehensiveness, but also the performance in term of de-biasing (here we address research question 2). Hence, we have a method that enables us to address the two research questions.

Step 3: maintaining Wald's formal model of decision-making within an extended generative perspective.

To apply this method, we need a formal model of a decision situation. As noted above, there are several candidates. Studies on strategic decision-making tend to refer to Savage's decision theory (Dean & Sharfman, 1996; Pich *et al*., 2002; Feduzi and Runde, 2014; Huang & Pearce, 2015; Feduzi *et al*., 2016). However, in this study, we rely on Wald's model. There are several justifications for this choice.

Savage's model is actually a generalization of Wald's model. Thus, what do we stand to lose by relying on

Wald? The main claim of Savage's decision theory is that if agents' preferences and beliefs are consistent (in the sense specified by Savage's axioms), these preferences may be represented by the expected utility formula, whereas Wald considers that the loss function and the beliefs are provided by the agent. As noted by Giocoli, the reference historian of decision theory, 'Savage's theory is first and foremost a normative guide to the formation of consistent beliefs' (Giocoli, 2013: 74). Relying on Wald, we consider that the belief and loss functions are *given*, and do not consider how they can be revealed by the choices made by the agents. By doing this, we avoid the question of whether the consistency rules required by Savage's axiomatic can be applied effectively.

Wald's model not only served as the foundation for Savage's model but was also the foundation of Raiffa and Schlaifer's (1961) model, which has been widely acknowledged in the management literature (Giocoli, 2013). Wald's analytical framework has been implemented in decision trees, which are still taught in many business schools and are the backbone of many studies on strategic decision-making (e.g., studies on real options). Hence, Wald's model can be considered as the operational basis of decision theory.

Wald developed his theory with the aim of providing an integrated framework for statistics, and in doing so he provided a model for making decisions in the face of uncertainty. For Wald, 'a solution to a statistical problem must instruct the statistician about what to do, i.e. what particular action to take, not just what to say' (Giocoli, 2013: 13). Hence, Wald's model is one of *action*, which suits our purposes.

We could also rely on a Simonian model of 'bounded decisions.' This path has already been largely explored, in particular with a view to finding ways to get closer to the optimal choice (as defined by Wald). Since the part of the path from 'bounded' to 'ideal' has already been widely discussed, we prefer to focus on the part between 'ideal' and 'extended ideal.' Using the 'ideal decision' as the starting point helps us to focus the generativity process on the phase that has been least explored until now.

To conclude, we apply C-K design theory to Wald's decision-situation model (the next section), and this formal approach provides answers to our two research questions (the following section).

A comprehensive and generative model for designing decisions in the unknown: properties and evaluation

In this part, we apply C-K design theory to Wald's decision-situation model. Our aim is to identify the possible extensions of decision theory using design theory. Following the C-K framework, we first identify precisely the 'decision model' that is in K_0, which reminds us of the basics of Wald's statistical decision theory. Then, we describe the C-space and the expansions (see Figure 4 for an overview).

Background: Wald's statistical decision theory and K_0

Wald formulated the basic decision problem as follows (Ferguson, 1976; Giocoli, 2013;). There are four components: (1) the available actions; (2) the states of the world (also called states of nature), one of which is the true one (the parameter space); (3) the loss function (also called the cost function) measuring the loss to the statistician if he or she takes a certain action when the true state of the world is given; and (4) an experiment, whose goal is to help the statistician to reduce the loss and whose results (called observations) depend on the true state. A decision function is a rule associating an action with each possible experimental outcome. The available decision functions are evaluated according to the expected loss their adoption may cause under the various possible states. The statistician's task is then to choose the decision function capable of minimizing the expected loss. Wald was able to solve this problem in very general terms by adding some additional ingredients: there is a loss function defined over each pair (state of nature and action), and the experimenter may have *a priori* distribution over the parameter space (belief about the states of nature, modelled with Bayesian formalism).

It is worth noting, after Gilboa (2009: 40), that Wald uses a Bayesian approach in the strict sense of statistics: 'Anything that updates a prior to a posterior based on evidence is referred to as 'Bayesian' while in economics the term refers to a more demanding ideological position, according to which anything and everything that is not known should be modelled explicitly in a state-space model and be subject to a prior probability'. Of course, in this study, we stick to Wald's approach and carefully avoid the economics position that hides the issue of the unknown or, said differently, codifies unknowns systematically in an a priori distribution (usually called uncertainty), which is a considerable restriction.

Wald's result (presented formally in Appendix A-1) is extraordinarily general: given the learning capacities L, *a priori* belief μ about states of nature θ_j in Θ, the set D of alternatives d_i, and the cost function C (d_i, θ_j), there is always an optimal choice function to identify the optimal decision d_{opt} inside the set of all known decisions D.

Let us take a very simple example: the raincoat/hat decision problem (see Figure 2). This is actually the example given by Savage when he discussed Wald's theory in his famous article (Savage, 1951). This example was used to show how Wald's theory, which was initially

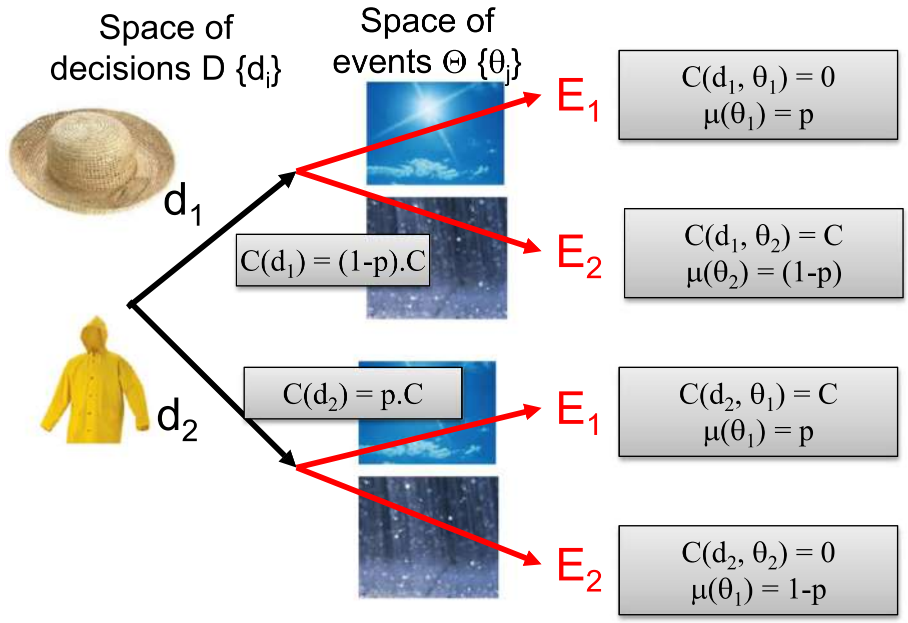

Figure 2 Decision tree for the raincoat/hat case (simplified: without sampling). [Colour figure can be viewed at wileyonlinelibrary.com]

thought of as a generalization of statistical problems, could be applied to simple everyday decisions.

The possible decisions are: d_1, take a raincoat on a walk; d_2, take a hat on a walk. The states of nature are: θ_1, there will be rain during the walk; θ_2, there will be sun during the walk. The beliefs are the probability of rain during the walk $\mu(\theta_1 = 1, \text{rain}) = \mu(\theta_2 = 0, \text{no sun}) = p$ (for instance 50%) and the probability of sun during walk $\mu(\theta_1 = 0, \text{no rain}) = \mu(\theta_2 = 1, \text{sun}) = 1\text{-}p$. The costs are, for instance, $C(d_1, \theta_1) = C(d_2, \theta_2) = 0$ and $C(d_1, \theta_2) = C(d_2, \theta_1) = C > 0$ (cost of taking a hat and it rains or cost of taking a raincoat and it is sunny).

Without sampling, the expected costs are (1-p).C for d_1 and p.C for d_2. If $p>50\%$, then choose d_1; if $p < 50\%$, then choose d_2 (given the limited space, we do not include the sampling case (see Appendix A-3)).

Generating new concepts of decisions (C-space): casting decision-making theory into design theory

Following the method presented in the previous section, given Wald's statistical decision problem in K_0, we actually *design a better decision situation* using C-K design theory.

In C-K design theory, the design process begins with a knowledge base K and concepts C. Knowledge K_0 is: D, the set of decisions d_i, Θ, the set of states of the world θ_i, and $C(d_i, \theta_j)$ and $\mu(\theta_i)$, which can be seen as 'properties' of d_i and θ_j. There are even definitional properties, *since* θ_i *and* d_j *only 'exist' in the problem through* C *and* μ. L(d, X) models the way to learn with X on θ_i to decide d_j, namely, how beliefs evolve by sampling.

The concept C_0 is: *from the given problem characterized by (D, Θ, μ, C, L), design a better decision situation*.

From this initial situation, the C-K design process leads to several better decision situations. The details of the construction of these better decision situations are presented in Appendix A-1. Below, we present the main features that are deduced from this construction and illustrate them using the raincoat/hat case.

Let us begin with the illustrative case. From the initial decision situation (see Figure 2), C-K design theory leads to the graph shown in Figure 3. In C, there are several concepts of better decisions. Note that even if we added some pictures, these are only concepts of decisions, that is, what is designed is a decision situation (not a product) represented by a decision tree, where some branches have yet to be fully designed to become an actionable decision. Here, we briefly describe Figure 3.

To design a better decision situation, C-K theory prescribes that we should rely on knowledge in K_0. Hence, we can think of designing a new decision d* in D. For instance, this can be to take another accessory that is better than a hat. This can simply be 'a better hat' that provides a bit of fun, even in the rain, hence the cost of having such a hat in the rain decreases (symmetrically, one could also design a better hat in the sun or a better raincoat in the sun or a better raincoat in the rain).

Then, C-K theory prescribes that we should use other pieces of knowledge (from K_0) to design new options. The knowledge on belief can be used: can one design a new decision that would be good *regardless of what one believes*, that is, an accessory that would be equally effective as a hat in the sun and a raincoat in the rain?

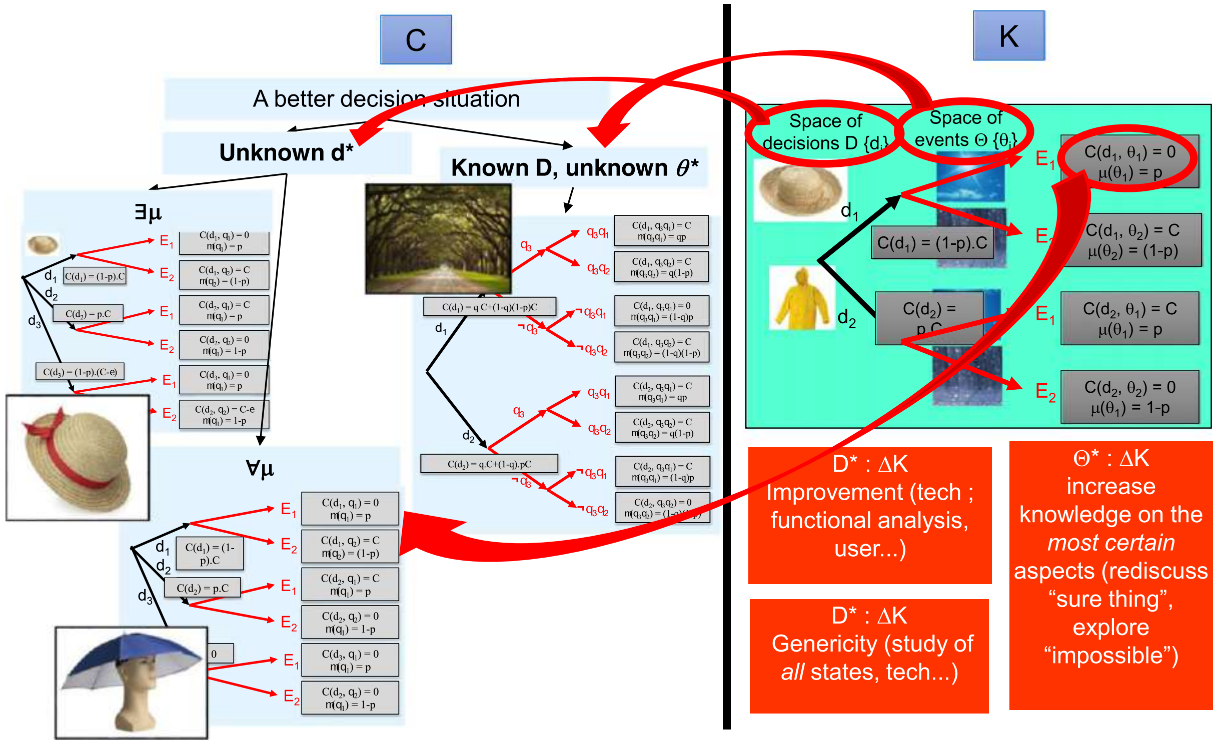

Figure 3 Extension of the raincoat/hat decision situation to the unknown – design paths toward a better decision situation are represented in the C-space; knowledge expansions appear in the K space. The red arrows represent the attributes of the initial knowledge (D, Θ and μ) that are used to generate the new design paths. [Colour figure can be viewed at wileyonlinelibrary.com]

We are now dreaming of something that could be called a ‘raincoat-hat’ that might not yet exist, but might be able to be created! This ‘chimera’ is represented by the illustration in Figure 3.

Finally, C-K theory prescribes that we should use a parameter that has not yet been used: design a better decision situation by using knowledge *on the space of events*, namely, by designing a new event! Of course, it might sound strange to suggest that we ‘design a state of nature,’ but we should keep in mind that from the Bayesian perspective, the state of nature is actually the representation of nature by the decision-maker. Hence, we can proceed with this hypothesis and imagine what new states of nature can be designed. For instance, one can look for a state of nature that would increase the costs of all known decisions, namely, hat or raincoat. Driven by this ‘unknown state’, one can consider that there are trees all along the walk that protect us from both the rain and the sun, making the hat and the raincoat useless accessories. In this case, we have added a new state of the world that changes the decision situation (other examples are given in Appendix A-1).

This example illustrates the main features that appear in the formal construction of the extension of a decision situation to the unknown. Let’s summarize now these features (a detailed demonstration is presented in Appendix A-1):

- We systematically identify all possible ways to generate new decisions d* that improve the decision situation, while keeping unchanged the states of the world. d* is better than the known decisions d_i.
- In particular, one design path generates a *generic* decision, that is, a decision that is good for *all* states θ_i of Θ. d^* is different from all combinations of d_i in D and addresses all known θ_i, i.e. d^* is generic to all θ_i. Note that ‘generic’ is strongly different from generative. Generic refers to the logic of ‘generic technology’ (Hooge et al. 2016, Kokshagina 2014, Le Masson et al. 2016b) or general purpose technologies (Bresnahan & Trajtenberg 1995, Joerges & Shin 2018): these are specific types of innovation solution that can address a large set of applications. A generic decision is hence a decision that is robust to several states of the world.
- The design paths will necessarily create new knowledge, and the learning process is guided by the design path: either it is led by d_{opt}, the optimal decision in the initial decision situation, or it is led by the systematic study of all θ_i to obtain a generic solution.
- The ‘decision designer’ can also create new decision situations by designing new states of nature θ^*. This is a generalization of the Bayesian approach from a belief in the probability of the occurrence of known states of the world to a belief in new, previously unknown

alternatives. The associated unknown might be either desirable (increased value) or undesirable (decreased value).

- The new state θ^* is a new dimension added to Θ. One important property is that it is generated by questioning the 'sure thing' or the 'impossible,' and not by reducing uncertainty.
- θ^* increases global uncertainty and might change the initial hierarchy between decisions d_i.

Using C-K design theory, we have systematically generated an extension of a Wald decision model under uncertainty. We can now analyze how this newly constructed decision-design model answers our research questions.

Findings and results: generating new types of decisions and revising states of nature

We obtain results in relation to our twofold research question: how to characterize the types of unknowns considered as directions of generativity (with associated value and type of knowledge to be explored) (RQ 1), and how to characterize the performance of the process of extending the decision situation to the unknown (RQ 2).

Types of unknowns corresponding to different directions for generativity (RQ 1).

Based on the model, we are able to identify, in the decision-challenging unknown, what we call decision concepts or *decision-driven design paths*. These are not decisions; they are decision-driven directions for the generation of a better decision situation. A decision-driven design path is still partially unknown, but it has two critical properties:

1. one knows more about the value associated with it (how much it will change the initial decision situation, measured in terms of expected utility); and
2. one knows about the knowledge that should be explored for the generation of the associated decision situation.

This a critical contribution: it becomes possible to *orient and stimulate* the generation process using decision-driven knowledge. In other words, knowledge about the decision situation does not necessarily restrict the generation of new decisions.

The model enables *four types of decision-driven design paths* (see the synthesis in Figure 4 and Table 1). The first two can be characterized as 'wishful decisions':

1. decision-driven design path, type 1: *new wishful decision by improvement* (Hatchuel *et al.*, 2011a) (unknown decision d^*, exploration driven by θ_{j0}). This consists of designing a new decision d^* as a variation of decision d_{opt}, which was initially identified as the best one. The design process is driven by a desire to reduce the cost of a specific θ_{j0}, $C(d_{opt}, \theta_{j0})$. The value of the unknown is given by $C(d^*, \theta_{j0}) < C(d_{opt}, \theta_{j0})$ and knowledge creation is driven by θ_{j0}. This is the most self-evident extension.

   Note that the value of knowledge is *not* in risk reduction (as in the basic model of decision under uncertainty) but in *cost* reduction associated with the new pair $(C(d^*, \theta_{j0}))$ (the probability associated with each state remains unchanged). In other words, we have a new way to value knowledge creation: decision theory under uncertainty provides a very interesting way to value knowledge creation through risk reduction; in this decision design, one can value knowledge creation in terms of the cost reduction induced by the newly generated alternative.

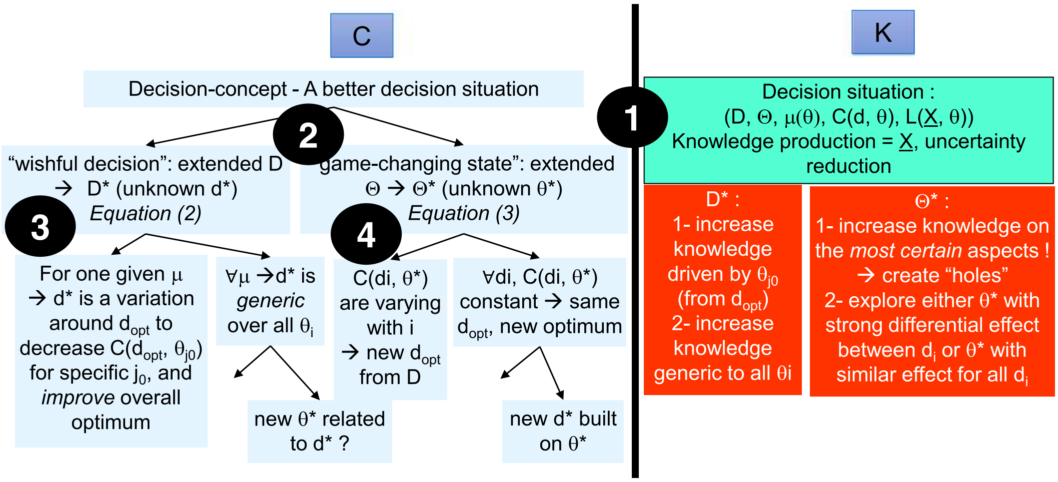

Figure 4 Decision design in the unknown. C shows the new decision-making situations after d^* or θ^* extension. K shows the knowledge creation strategies associated with the design of d^* and θ^*. Numbers 1 to 4 indicate the possible fixations. [Colour figure can be viewed at wileyonlinelibrary.com]

Table 1 Decision design in the unknown: the main features of the four decision-driven design paths (first column: reference = reduction in decision theory)

	Reference: learning in decision theory in uncertainty	*New, wishful decision by improvement*	*New, wishful decision by genericity*	*New, decision changing state by best choice hacking*	*New, decision changing state by all choices hacking*
Unknown?	No unknown, only uncertainty	New decision d*	New decision d*	New state θ*	New state θ*
Driver for the exploration of the unknown	Learning based on risk reduction (sampling to change the belief from a priori to a posteriori)	Better than the (initially) optimal one d_{opt} on at least one state of the world θ_{j0}: $C(d^*, \theta_{j0}) < C(d_{opt}, \theta_{j0})$	Better than all decisions in all possible states $\forall i, \forall j\ C(d^*, \theta_j) < C(d_i, \theta_j)$	Explore the 'most certain knowledge', the 'impossibles' associated to the best decision d_{opt}.	Explore the 'most certain knowledge', the 'impossibles' associated (systematically) to all decision d_i
Value of knowledge	Decrease expected costs	Not in risk reduction, but in decision improvement	Not in risk reduction, but in genericity	Not in risk reduction but in identification of new specific risk	Not in risk reduction, but in identification of new systemic risk

2. decision-driven design path, type 2: *new wishful decision by genericity* (unknown decision d^*, *independent of all* θ_i). This consists of designing d^* as a *generic* alternative that is better *whatever* the state θ_i. Knowledge creation is driven by this genericity, either independent of all θ_i or driven by features that are common to all θ_j.
   Again, the value is not in risk reduction. The *value of the knowledge creation is all the higher that* d^* *is independent of all* θ_i. *The value of the knowledge lies in the new interdependence of* d^* *and* θ_i (in terms of costs $C(d^*, \theta_i)$). Note that this form of extension is not really examined in the literature on the unknown in strategic management; it is more common in the literature on platforms and the management of generic technology (Bresnahan and Trajtenberg, 1995; Gawer, 2009; Kokshagina *et al*., 2017a). We can see how the systematic framework unifies different types of unknowns and different types of exploration strategies.

The two other decision-driven design paths rely on the design of a new state of the world that will change the decision situation. We call them design paths toward a decision-changing state.

3. decision-driven design path, type 3: *new decision-changing state by 'best-choice hacking'* (unknown state θ_i^*, exploration driven by having a differential effect on d_i). This consists of designing θ^* as a new dimension of the states of the world that changes the hierarchy between decisions d_i. Knowledge creation is driven by investigating the most certain knowledge (sure thing) and by the search for the most order-changing state (heterogeneous $C(d_i, \theta^*)$). The value of knowledge relies on *new interdependencies* between d_i and θ^* (in terms of expected costs $\sum_{j=1\ldots n+1} C(\theta_j, d_i)\mu^*(\theta_j)$). This corresponds to 'uncovering unk-unks' by studying the *robustness of a single solution* (for instance, the dominator, i.e. the best one). In particular, this corresponds to the try-and-learn processes described by (Loch *et al*., 2008). Additionally, it helps orient the exploration process: the model shows that these 'best-choice hacks' can be found when looking at the most certain knowledge. The model does more than merely facilitate broad exploration; it prescribes that we should *focus on the most certain knowledge*, in other words it recommends that we look at impossible states (those that are certain not to occur) and not at the probably possible ones. Again, this underlines the fact that the issue is not in uncertainty reduction, but in unknownness exploration.

4. decision-driven design path, type 4: *new decision-changing state by 'all-choice hacking'*

(unknown state θ^*, exploration driven by having a systematic effect on all d_i). This consists of designing θ^* as a new dimension of the states of the world that does not change the hierarchy between decisions d_i but changes the overall value. Knowledge creation is still driven by investigating the most certain knowledge (sure thing), but it is also driven by a search of the non-order-changing states (homogenous $C(d_i, \theta^*)$). The value of knowledge relies on *new interdependencies between* θ^* *and existing* d_i (in terms of expected costs $\sum_{j=1\ldots n+1} C(\theta_j, d_i)\mu^*(\theta_j)$). This also corresponds to 'uncovering unk-unks,' this time through a parallel exploration. However, this is a parallel exploration where the generator looks for systematic conditions that will impact *all* solutions, either positively or negatively. Hence, the model leads us to focus on the hidden interdependencies that make all known states and all known decisions work together (e.g., one designs the 'walk under trees' situation by trying to find a case where, regardless of the decision between a hat or a raincoat and the state of nature, i.e. rain or sun, the pair decision state will be bad).

We synthesize these four decision-driven design paths in Figure 4 and Table 1. The model shows the four archetypes, but combinations are of course possible. In particular, the generation of a new alternative can lead to the generation of new states (at a new level in the tree, see Figure 4) and the generation of new states of the world can lead to the generation of new decisions (see Figure 4).

Characterizing performance levels by types of generative biases (RQ 2)

The model underlines a general increase in comprehensiveness. In each branch, there is a gain in D and/or Θ. This is possible because the generation model retains the decision logic. It does not end with a list of 'ideas,' but each branch retains the decision-making formalism. In particular, this means that in each branch, it is still possible to compute the best solution according to Wald's model. One simple consequence is that the decision models that are already in place in a company are preserved and enriched by the generativity process.

However, one should note that between the initial and final states, there might be some surprising changes. For instance, the model shows that the value of the best decision might be *lower* after the generation process. This is linked to the fact that the generation process actually leads to a *transformation of unknownness into uncertainty*, thereby increasing uncertainty. One direct consequence of this is that the expected value of the best alternative cannot be taken as an indicator of the increase in comprehensiveness. Thus, we should look for other indicators of performance improvement.

Another indicator of the performance of the generativity process is the capacity to map fixation and defixation areas. We now show how the model sheds light on the generation biases associated with the process of extending a decision situation to the unknown.

Overcoming bias in favor of uncertainty and against the impossible. The decision-design model helps to overcome a first-generation bias that comes from the distinction between decision under uncertainty and generation under uncertainty: individuals and teams might tend to represent themselves as *deciding* under uncertainty instead of *generating*. Technically, referring to Figure 4, it means that they tend to stay in K instead of going to C. In K, they produce knowledge for uncertainty reduction, and they are certainly not producing knowledge that enables them to rediscuss sure things. Many studies have discussed this type of bias: business plans based on optimal NPV expectations, project management dealing with uncertainty instead of unknownness (Lenfle and Loch, 2010), the dangers of misleading expectations in technology development (Borup *et al.*, 2006; Geels and Raven, 2006; van Merkerk and Robinson, 2006), and decisions in relation to innovation projects (Elmquist and Le Masson, 2009).

Overcoming bias in favor of problem solving and against environmental exploration (problem finding). If one supposes that a team is designing an innovative solution, a second fixation appears in relation to the alternatives D^* vs Θ^*. Some teams will be tempted to look for new decision alternatives d^* and will neglect the possibility of designing (discovering) new states of the world θ^*. This might be the case for engineering departments that design products when external conditions Θ are given by the list of requirements. Conversely, some teams might be tempted to design new θ^* for a given list of possible decisions D. For instance, this might occur when a commercial department tries to find new markets without changing the firm's technologies and products. In general, one tends to see a bias in favor of problem solving and against environmental exploration, which corresponds to problem finding. (von Hippel and von Krogh, 2016) examine multiple studies that underline the risk of fixation on a problem that is not well formulated and is not regenerated (von Hippel and Tyre, 1995; Sieg *et al.*, 2010; Sieg, 2012). By mapping both processes, the model contributes to overcoming fixation.

Overcoming bias in favor of optimizing for one known condition and against the design of generic solutions. Suppose a team is designing a new decision d^*: there is a possibility of fixation on designing d^* that optimizes d_{opt} on one (or a couple of) θ_j ; the team will hardly consider designing a d^* that is independent of external states of the world, i.e. external demands. That is, there is a fixation on designing specific, targeted products/services instead of designing generic solutions (Hooge *et al.*, 2016; Le Masson *et al.*, 2016a; Kokshagina *et al.*, 2017a).

Overcoming bias in favor of increasing robustness of one known solution and against the discovery of systemic risk. Suppose a team is now designing new states of the world θ^*: there is a possibility of fixation on testing whether d_{opt} is *robust* under alternative conditions θ^*. Hence, one is looking for specific θ^* where $C(d_i, \theta^*)$ are so different that they could change the hierarchy of decisions. Teams and individuals will less readily explore situations that *systematically* impact the overall value (and would ultimately lead to a new d^* associated with θ^*), that is, the investigations to uncover systemic risk are hindered by generation bias (Loch *et al.*, 2008; Lenfle and Loch, 2010).

We can see how many well-known tensions, dilemmas, or biases in innovation management can actually be mapped as generation biases in an extended decision-making framework.

Discussion and conclusion.

This study contributes to innovation management and the foundations of management science. Methodologically, it shows how progress in innovation management and design theory enables us to formally approach the question of the extension of decision-making to the unknown. Subsequently, the study proposes a model of decision design in the unknown with a clear rationality model and explicit performance. The main features are summarized in Table 2, which compares the model of decision under uncertainty with that of decision design in the unknown.

Based on the proposed model, this study contributes to the twofold issue of the unknown in decision-making: (1) the paper identifies a structure of the decision-oriented unknown based on four contrasting types of actionable unknowns called decision-driven design paths and clarifies how each type relates to a particular logic of decision-oriented generativity, with a specific value and specific types of knowledge expansion (synthesized in Table 1); and (2) the study identifies the performance associated with the exploration strategies, this performance being assessed in terms of defixation, that is, the capacity to overcome generation bias. We synthesize this contribution in Table 2. This raises two discussion topics that also indicate directions for further research.

The potential contribution to Artificial Intelligence (AI) of the new model of decision-oriented generativity

The structure of the unknown was obtained through a formal approach. Before discussing further organizational issues, it is interesting to note that a formal approach can also have intrinsic value. Today, decision theory is implemented in many algorithms (particularly in AI approaches) and leads to significant dilemmas. One example is the study we referred to in the Introduction (Bonnefon *et al.*, 2016): how should the algorithm 'decide' (*in the strict sense of a formal decision-making model*) when confronted with a dilemma such as 'If the brakes have failed, should the driver of the car kill the pedestrians crossing the street or save the pedestrians by crashing the car into a wall, thereby killing the occupants of the car?'

Formally speaking, this dilemma can be avoided by extending decision-making to the unknown, and our model indicates four design paths. This induces a question: can one implement an algorithm that corresponds to these four design paths to enable a machine to generate a new path? Interestingly, recent progress in AI (in particular on novelty searching or MAP-Elite algorithms) is enabling machines to invent new behavior when confronted with unexpected events (see Lehman and Stanley, 2008; Cully *et al.*, 2015). Our model of decision design in the unknown might make it possible to systematize the analysis of all the

Table 2 From decision model to decision-oriented generativity model: a new rationality model and associated performance

	Model of decision under uncertainty	*Model of decision design in the unknown*
Rationality model	If there is: - a set D of decisions d_i, - a set Θ of probable states of nature θ_j, with a belief function μ, - and a cost function $C(d_i, \theta_j)$ (and a learning function L) → then there is an optimal decision diopt that minimizes cost function	If there is D, Θ, μ, C – but the optimal decision is not desirable, → Then there are four decision-based design paths to generate a better decision situation that extends the given one and this better decision situation: -New, wishful decision by improvement -New, wishful decision by genericity -New, decision-changing state by best choice hacking -New decision-changing state by all choices hacking
Performance	Overcome selection biases	Overcome generation biases

design paths that a machine might generate and/or analyze the possible generation biases in generative algorithms.

Revisiting organizational issues raised by the unknown.

The question of managing in the unknown is one of the critical issues of management science. Since the 1960s, management science developed rational models of action with *uncertainty*. The development of the theory of decision under uncertainty provided then management with ‘the basic disciplines that underlie the field of business administration’ according to Bertrand Fow, the Director of Research at Harvard Business School in his preface to the reference book ‘applied statistical decision theory’ of Raiffa and Schlaifer (1961). The theory of statistical decision-making provided an integrated framework that could account for choices between known alternatives, taking into account uncertain events. Moreover, the models were able to place a clear value on uncertainty reduction endeavors (leading to option theory and later to real options), and this also led to powerful organizational models in which expertise, knowledge, and competences appear as core resources for dealing with uncertainty (see, for instance, the classical synthesis of organizational forms by Mintzberg (1978, 1979). Recent studies by historians and economists on the origins of decision-making in economics have led us to think that decision theory under uncertainty was one of the notions that was born in management before being applied to economics (Giocoli, 2013). Following these works, decision appears as a general pattern in decision-based organizational language:

- There is a clear managerial goal, namely, to select the best decision by overcoming selection biases.
- There are two main types of actors: decision-makers and experts, the latter making systematic preliminary investigations to prepare the ground for rigorous, objective decision-making by the former.
- There are techniques and instruments for evaluating alternatives (such as expected NPV) and there is a value ascribed to knowledge resources: knowledge reduces risks (e.g. R&D and marketing studies) and reduces selection bias, enabling a decision that is as close as possible to the optimal choice for a given actor. (see table 3, second column).

Since the unknown is seen today as the type of situation that cannot be handled by the usual decision-making framework (Loch *et al*., 2006), it implies that the unknown might represent a situation in which organizations are at their limit. When organization theory is at its limits, should one rely on the market when facing the unknown? Some studies, particularly in economics, follow this track and analyze open innovation, contests, crowdsourcing, start-up development, or ecosystems strategies as ways to deal with the unknown (e.g., Terwiesch and Xu, 2008). Other works (e.g. Wideman, 1992; McGrath and MacMillan, 1995, 2009; Pich *et al*., 2002; Loch *et al*., 2006, 2008; Cunha *et al*., 2006; Mullins, 2007; Weick and Sutcliffe, 2007; Sommer *et al*., 2008; Rerup, 2009; Feduzi and Runde, 2014 Feduzi *et al*., 2016) suggest that managing in the unknown leads to the development of *new formal models of rationality* that take into account the unknown and that are related to new forms of organizations. In that sense, managing in the unknown is the new frontier of management science.

This study has followed the latter approach by presenting a formal model of rationality to generate a structured mapping of exploration trajectories in the unknown (four decision-driven design paths). Even if

Table 3 How the model of ‘decision design in the unknown’ helps underline some differences between ‘decision based’ organization and ‘decision-design based organization’

	Some features of an organization based on decision under uncertainty	*Corresponding features in a organization based on decision design in the unknown*
Management (leadership, processes, competences, organizations…)	Principle: organize to select the optimal decision by overcoming selection biases	Principle: organize to generate a better decision situation by overcoming generation biases
	Organization and capacities: *decision makers & experts* – experts gather relevant data to check D, Θ, μ, C and learn in order to reduce risk (R&D, marketing, etc.);	Organization and capacities: *capacity to generate pathes*: ‘exploration’, ‘dynamic capabilities’, ‘ambidexterity’, ‘innovation function’,… *manage multiple coordinated explorations*: ‘agile’, ‘flexible’, ‘open’, ‘co-’, ‘platform based’, ‘flexible’, ‘parallel / sequential’,…
	Quality process and techniques: systematic preliminary investigation + decision based on rational criteria (rely on techniques to evaluate cost function: NPV, etc.)	Quality process and techniques: systematic actions to generate new decisions and new representation of states of the world + governance of the exploration*s*. Requires a mix of valuation techniques and generation techniques.
	Value of knowledge: risk reduction and selection bias reduction (as close as possible of the optimal choice)	Value of knowledge: improved optimal choice *and* improved representation of states of the world – generation bias reduction

it is beyond the scope of this study to analyze all of the implications for organizations, it is important to identify some consequences related to organizational capacity that are associated with the formal framework (see Table 3, third column): The extension of the model of decision under uncertainty to a model of decision design in the unknown leads to a discussion of the related generativity capacities in the organization. These capacities echo well-known notions in the literature such as dynamic capabilities (Teece *et al*., 1997; Eisenhardt and Martin, 2000), ambidexterity (Duncan, 1976; Tushman and O'Reilly III, 1996; Birkinshaw and Gupta, 2013), agile and flexible development (MacCormack *et al*., 2001), and parallel/sequential learning (Loch *et al*., 2006):

- Similar to the decision model for decision capacities, the generativity model induces *quality criteria* in relation to generativity capacities: There is *a clear managerial goal of generating a better decision situation by overcoming generation bias*.
- This leads us to distinguish the capacity to *generate a new path and the capacity to manage multiple coordinated explorations*. The former should enable a systematic exploration of new decisions *and* new states of the world, while the latter should organize and control generation biases, in particular by covering the four archetypal decision-oriented design paths.
- There is a *value ascribed to knowledge resources*: knowledge reduces generation biases and generates improved choices.

This analytical framework, deduced from the generativity model, might help us to characterize the quality of generativity capacities and provide formal grounds and criteria for analyzing the notions evoked above: dynamic capabilities, ambidexterity, agile and flexible development, and parallel/sequential learning.

To conclude, this study aims to contribute, at least partially, to a revision of the foundations of management science by exploring the logic of the unknown in management science. The unknown is the new frontier for management and organizations. Since organizations struggle to manage the unknown, they are tempted to rely on the market to deal with situations involving too much that is unknown. Our study shows that innovation theory and design theory can provide us with formal models that help us to think about and characterize the logic of managing in the unknown. This model of decision design makes the unknown actionable via decision-driven design paths that orient the generation of *better* decision situations and help to overcome dilemmas and generation biases. It is interesting to note that these generation biases might actually be caused by management science itself. This means that, in a sense, these formal models also contribute to protecting management science from its own fixation![1]

More generally, this study contributes to the large body of work confirming that management is no longer limited to the decision-making paradigm, but is already in a post-decisional, generativity-based paradigm wherein models of collective action in the unknown are the new frontier. These studies contribute to making management science one of the few disciplines that is able to scientifically address the issue of the unknown, its language, its structure, and its specific logic of action. They contribute to the repositioning of management science as the discipline underlying the construction of a desirable unknown.

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Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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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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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.

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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-

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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 π 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 Π.
- An evaluation function γ on the elements of Π which calculates the overall quality $\gamma(\pi)$ for each possible sequence π 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:

$$min\ \{\gamma(\pi) \mid \pi \in \Pi\} \qquad (1)$$

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].

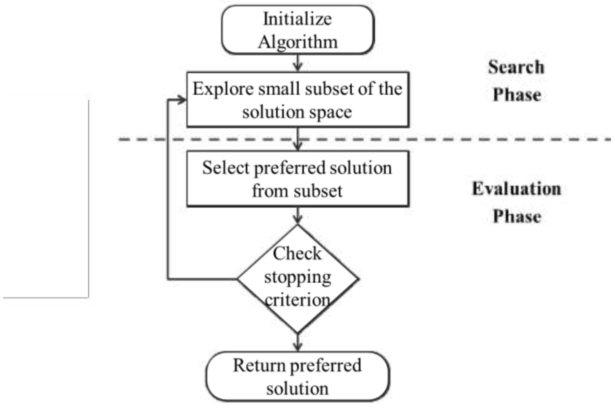

Fig. 1. Principle of iterated search

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.

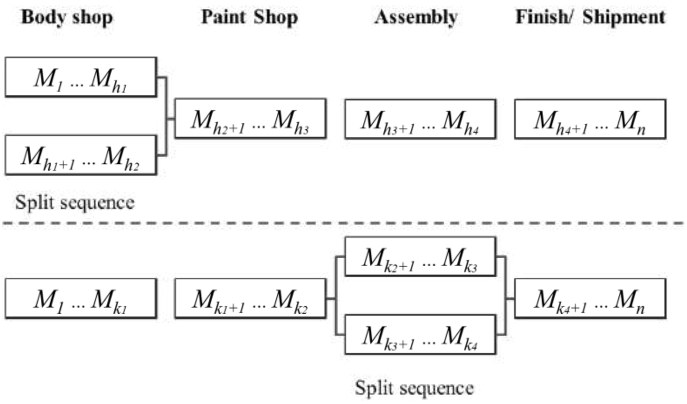

Fig. 2. Examples for different plant layouts

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.

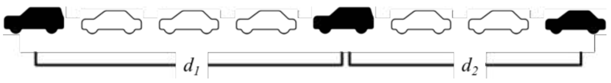

Fig. 3. Illustration of distances in the sequence

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 distribution of certain types of orders across the sequence to smooth parts supply.

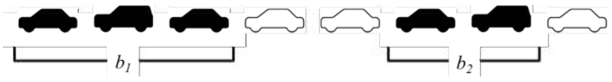

Fig. 4. Illustration of batches in the sequence

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.

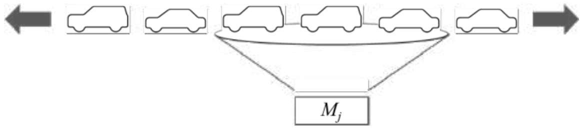

Fig. 5. Illustration of workload per station

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.

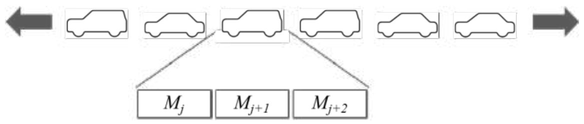

Fig. 6. Illustration of workload on consecutive stations

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.

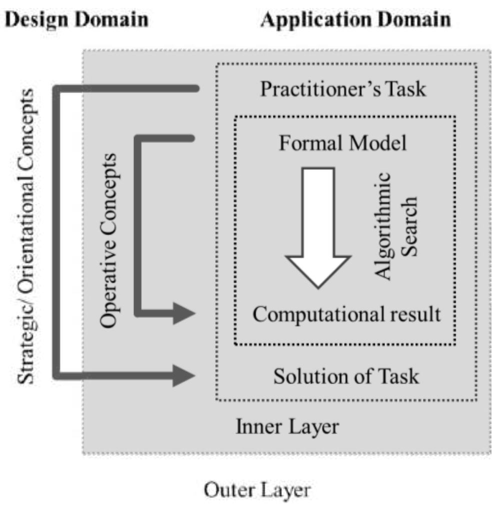

Fig. 7. Principle of iterated search

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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INDUSTRIALISING INNOVATION IN DIGITAL MANUFACTURING WITH AUTOMATED SEARCH – A DESIGN-BASED APPROACH

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Abstract

The increasing availability of comprehensive digital models of manufacturing and other contained industrial operations creates potential to apply automated search procedures for innovation purposes. Such procedures are already well known from the context of operations research. This paper investigates how they can be related to the wider scope of innovation. The theoretical background is provided by C-K Theory, which allows the distinction of different operations in the course of innovation regarding knowledge and concept generation. Using the prominent example of genetic algorithms, the paper discusses different steps of automated search procedures in relation to C-K theory and its underlying considerations in formal-symbolic logics and set theory. The results show many correspondences between the search logic and innovation, particularly in the constructive approach to concept generation. The findings suggest that the usage of automated search procedures for innovation will have a layering effect on the different operations which are involved, which is in some respect similar to industrialisation patterns from the early 20th century, but completely different regarding the treatment of knowledge.

Keywords

C-K Theory, digital transformation, manufacturing, heuristic search, industry 4.0, artificial intelligence.

Introduction

Since the early days of modern research on artificial intelligence, scholars have thought about the possibilities of machines to be creative. A recent exhibition called “Artistes and Robots”, the Grand Palais in Paris has presented an overview of different approaches to this topic. Most of them were based on comparably simple applications of technology to generate arbitrary object patterns as a new design option (see Figure 1). Today, however, new technology raises expectations that advanced algorithms can provide an even more powerful contribution in terms of creativity, which also bears the potential to give machines agency in innovation processes and challenge the authority of human beings in this context. The power of these algorithms has already been documented in many well-contained settings such as games like Chess or Go. This paper discusses applications of such algorithms in larger scenarios of innovation.

Figure 1 Early explorations of machine creativity: Jean Tinguely's Meta Matic (1959) from the exhibition "Artistes et Robots"at the Grand Palais, Paris/ the Musée Tinguely at Basel.

The increasing permeation of society with digital devices creates potential for the creation of new kinds of technical solutions and economic value streams (e.g. Lee, 2008; Porter and Heppelmann, 2014). Various scholars (e.g. Yoo et al., 2010; 2012; Fichman et al., 2014; Lusch and Nambisan, 2015) highlight the radical change of perspective in innovation management that goes along with this development. Ubiquitous technology makes it possible to conceptualize the all kinds of social phenomena as hybrid systems of cyber-physical operation (Lee, 2008), merging physical and symbolic representations of business operation in a single computational structure. Characteristic attributes of physical objects are comprehensively referenced in computational structures, with the aspiration of identifying any observable entity or event observable in the physical world with a data set and operation in an information system (Geisenberger and Broy, 2015). Digital representations can thus become the driver for innovation, allowing the exploration of arbitrary combinations of data sets and events to solve operative problems and create new offerings, thus leading to a new industrial revolution with unprecedented impact on all areas of human life (Lee et al., 2015; Jazdi, 2014; Kagermann, Wahlster, and Helbig, 2013; Rajkumar et al., 2010).

Scientific literature discusses the application of cyber-physical systems in contexts like automatization, autonomous operation, augmented and virtual reality, decentralised organisation, cyber-security, knowledge management and qualification (Oks, Fritzsche and Moeslein, 2017; see Table 1). While there are many different industries which are expected to benefit from the implementation of cyber-physical systems (Rehm et al., 2015), manufacturing seems a particularly promising field for innovation

(Brettel et al., 2014; Monostori, 2014). This can be explained by the fact that manufacturing takes place in a confined space with little interaction with the outside. It is therefore comparably easy to create comprehensive digital models of industrial operations in manufacturing and control their further development into a certain direction to capture new business opportunities (Chryssolouris et al., 2009; Bracht and Masurat, 2005).

Automatization	• Integrated flow of production • Machine-to-machine communication (M2M communication) • Plug-and-produce machinery interconnections • Automated guided vehicles (AGV)
Autonomization	• Supervisory control and data acquisition (SCADA) • Condition monitoring • System reconfiguration
Human-machine interaction	• Unrestrained human-machine collaboration • Robotic exoskeletons • Decision support systems • Resource cockpits • Augmented reality
Decentralization	• Decentralized computing in modular networks • Complex event processing
Digitalization for process alignment	• Digitalization of warehousing and logistics • Automated e-procurement • Industrial services in the field of maintenance, repair and operations (MRO) • Digital image of products • Document digitization
Big data	• Pattern detection • Data processing warehousing solutions
Cyber security	• Cyber security solutions • Engineering of safety system infrastructures
Knowledge management	• Systematic recording, categorizing and mapping of implicit knowledge • Action guidelines
Qualification	• Qualification concepts • E-learning

Table 1 Application domains for cyber-physical systems discussed in literature (from Oks et al. 2017).

Digital models of industrial operation have already assumed an important role for innovation in the context of manufacturing (Chang and Wysk, 1997; Groover, 1980). They support the search for new ideas and better problem solutions in at least three different ways:

- Digital models provide the basis for the analysis of business operations and value streams to identify opportunities for improvement and further development with the help of modern big data applications (Goelzer and Fritzsche, 2017).
- They create virtual environments in which expert and non-expert users can creatively work on innovation, using different kinds of digital toolkits, configurators and virtual design studios. (Scheer, 2012; Naik, 2017).

- They provide the basis for a completely automated algorithmic search for solutions to given problems, for example in the context of plant design and facilities management, inventory management, production design and planning (Tompkins et al., 2010; Nahmias, 2009; Silver, Pyke, and Peterson, 1998).

The ongoing digital transformation of industry will further expand the range of application of information technology in manufacturing and all surrounding processes. It will create new opportunities to interconnected systems architectures which take over different functions at the same time. Innovation will be increasingly supported by information systems, and a lot of activities in the search of new ideas and improvements will be performed automatically without active user involvement (Monostori, 2014).

The introduction of new machinery to support human work is a key feature of industrial development. So far, however, it was mostly directed as simple, repetitive tasks. Complex, creative processes like innovation are a fairly new terrain for technical support, but with the ubiquitous availability of digital technology, it might now gain momentum very fast. This paper therefore intends to explore how such an “industrialization of innovation” with the support of digital technology might proceed. The exploration draws on examples of existing technical support for problem solving in manufacturing to understand how the underlying algorithmic logic relates to innovation. More exactly, it looks at heuristic algorithms for automated search and optimization procedures which have already been recognized as tools for innovation (Goldberg, 2013; Fogel, 2006).

As a theoretical basis for the investigation, the paper uses C-K Theory of innovative design (Le Masson, Weil and Hatchuel, 2017), which allows the discussion of a variety of qualitatively different operations necessary for innovation. The analysis of the heuristic algorithms performed on the following pages shows that technical support changes the way how these operations are related to one another, creating different levels of design activity which have to be considered at the same time for digital innovation.

As this is a merely conceptual paper, the paper focusses on the discussion of algorithmic procedures according to the current state of the art in operations research and engineering (Gendreau and Potvin, 2010; Talbi, 2009; Yang, 2010; Goldberg, 2013). For illustration purposes, insights from practical application are also used which were gained during various research activities in the automotive industry (see also Fritzsche, 2009).

Theoretical background

C-K Theory of innovative design

The point of view which will be taken on the following pages is informed by the Concept. Knowledge Theory (or in short: C-K Theory) by Hatchuel and Weil (1999; 2002; 2009). The central element of C-K Theory is the interaction between two spaces of propositions: space K which contains what the authors address as knowledge, and space C which contains what the authors address as concepts (see Figure 2). According to Le Masson, Hatchuel and Weil (2017:126), “C-K theory proposes as unified a language as possible to facilitate dialog between the major design professionals, namely designers, engineers and architects, independently of the specific objects they design and handle”. Furthermore, the authors are also interested in economic questions related to design and the treatment of innovation as a design capability (e.g. Hatchuel, Le Masson and Weil, 2006; Hatchuel, 1999). The distinction between a knowledge space and a design space enables the authors to distinguish different kinds of operations in design and the reasoning processes they involve (see also Hatchuel, Le Masson and Weil, 2004; Agogué and Kazakçi, 2014). They will provide the point of reference for the further investigations in this paper.

In C-K Theory, the propositions in the space of knowledge K have a logical status, which the authors describe as the degree of confidence assigned to a proposition (Hatchuel, Le Masson and Weil, 2004). For the propositions in the space of concepts C, this is not the case. The logical status remains unclear. (Without exploring all the formal details, one might think of an empiricist as well as a rationalist interpretation of this situation: the former would refer to the propositions in K being satisfied by having the real world as a model, the latter would refer to the propositions in K being decidable on the background of a given set of axioms. For C, satisfiability or decidability would be missing.)

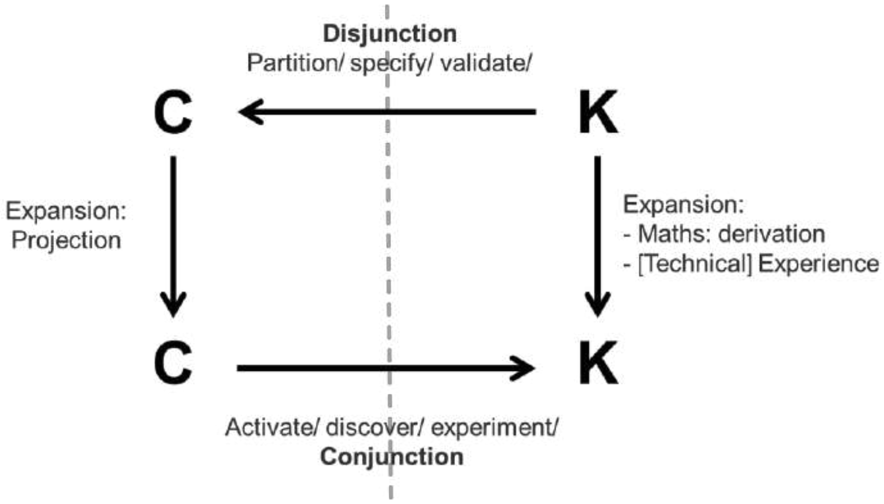

Figure 2 Simplified framework of C-K Design Theory (adapted from Hatchuel, Le Masson, Weil 2004)

C-K Theory defines design as the set of operations which are performed within C and K and between C and K. Roughly speaking, operations leading from K to C can be interpreted as a generation of alternatives or expression of possibilities on the basis of existing knowledge, but surpassing it. Operations leading from C to K can vice versa be interpreted as the introduction of a new artefact in the world as a product, service etc. which concludes a design process. Operations which proceed in C and K respectively are related to two different practices in mathematics: set theoretical operations lead to partitions, expansions, etc. of concepts in C, while logical rules and propositional calculus lead to conclusions/ proofs of new theorems in K. (The latter might again be interpreted from an empiricist perspective as an expansion of knowledge by the means of correct experimentation or as a mere formal, mathematical process from a rationalist perspective.)

Digital technologies and industrial innovation

The digital transformation of industry is enabled by important achievements in engineering regarding the development of sensors and actuators which allow the implementation of cyber-physical systems (Kagermann et al., 2013; Lee, 2008). The potential for innovation resulting from this development, however, has little to do with new technical devices. The so-called “digital innovation” (Fichman et al., 2014) is rather concerned with the integration of existing technology across larger organizational structures (Brettel et al., 2014), the creation of new business models (Porter and Heppelmann, 2014) and the establishment of systemic structures in which new services can be offered due to the interaction between different actors (Lee, Kao and Yang, 2014; Lusch and Nambisan, 2015). Digital innovation is in this respect closely related to many problems of facility and production management which have been discussed in the field or operations research for a very long time, such as the planning of jobs sequences in production, the design of manufacturing networks, or various routing and scheduling tasks related to it (Potts and Strusevich, 2009; Schrijver, 2005).

Such problems usually receive little attention in the field of innovation management, as they are expected to involve fairly little creativity, because the potential solutions of the problem are well known. They are either solutions of a given equation or elements of a search space whose elements can be clearly defined (Bixby, 2012; Graham et al., 1979). From a mathematical perspective, however, this appears to be true for most of the examples which are given for digital innovation in manufacturing. Inasmuch as manufacturing takes place in a contained environment, which is furthermore represented by a digital model, the number of solutions is finite. Without any further structural information, the number of atoms fitting in the physical space of a factory or the number of bits available for computation of the digital model can be used as rough upper bounds. It can in this sense be reduced to a mere combinatorial problem where general concerns about decidability or choice are irrelevant. Elements of finite spaces can be sorted and enumerated, which, given enough time and computing power, makes it possible to identify best elements with respect to any given information source which provides consistent information about preferences for all elements of the space. Furthermore, comprehensive digital models can be expected to allow simulations of industrial operation which provide statement about efficiency etc. as preference information. Big data analytics on customer behaviour can provide similar data from a marketing perspective.

Nevertheless, there is good reason to assume that digital innovation, like many instances or problems discussed in operations research, still involves creativity. Enumerations of the solution space may be possible in theory, but not in practice, because the number of possible combinations or permutations entities which need to be considered is not computable. While selection methods like branch and bound (Lawler and Wood 1966) can considerably reduce the effort under certain conditions, size and structural complexity can even turn simple combinatorial tasks into wicked problems (Rittel and Webber, 1973, Conklin, 2005), which makes it necessary to take refuge in heuristic search methods (Simon and Newell, 1958).

As a consequence, it seems possible to apply C-K Theory to combinatorial tasks in the context of the digital transformation as well – not from the point of view of general constructive set theory, but rather an intuitionist stance which replaces arguments based on the cardinality of infinite sets by arguments based on simple practicalities. It might be worth noting that the necessity to be creative in proving new theorems by the means of propositional calculus has been explained in a very similar way by Polya (1945).

Heuristic search and creativity

Based on the previous considerations, it seems appropriate to focus all further investigations in this paper on scenario of digital innovation involving algorithmic search with the following properties:

- Innovation takes place within a finite search space. The elements of the search space are different arrangements of resources and sequences of operations in which they interact. The space is well defined regarding its extension, inasmuch as the elements can be characterised as the set of all different combinations of resources and operations in the basis of a digital model of manufacturing.
- There is a function which returns consistent information about preferences for all pairs of elements from the solution space. To simplify things, this function is considered as a measure on the whole space. This function, however, may only be available as an “oracle”, which means that it can be called at any time, but its analytical properties remain unclear, like in the case of a complex factory simulation.
- The solution space is so big that an enumeration of its elements cannot be performed in due time. Furthermore, the topology induced on the space by the evaluation function is unknown, which means that there is no further information where good solutions can be found and how similar they are regarding the arrangements of resources and operations they express.

Under these conditions, innovation can be discussed as a search for best elements in the solution space. This fits to a long tradition of thought about innovation as a combinatorial task, ranging from Pappus over Leibniz to Weber (see Hubig, 2007).

In absence of information about the topological structure of the space in terms of solution quality and no possibility to process the space in its entirety, heuristic algorithms can perform an iterated local search to identify best elements of the solution space. The search can proceed in numerous different ways (Gendreau and Potvin, 2010; Talbi, 2009). One of the most popular approaches take to local search is known by the term genetic algorithms. Genetic algorithms are inspired by patterns of reproduction and selection studied in evolutionary biology (Holland, 1975). However, there are claims that genetic algorithms actually a general pattern of search and discovery found in numerous innovation projects (Goldberg, 2013), which makes them particularly interesting in the context of this paper. The operation of a genetic algorithm can roughly be described in the following way (cf. Mitchell, 1998):

1. A small subset of the solution space is chosen as the initial population for the search (arbitrarily chosen or informed by precious considerations)
2. From this population, new elements of the solution space are identified by performing simple combinatorial operations at random on the current population.
3. The external evaluation function is used to compare old and new solutions. The best ones are taken over to form the new population.
4. The algorithm iterates this process from step 2 onwards until some kind of stopping criterion is satisfied.

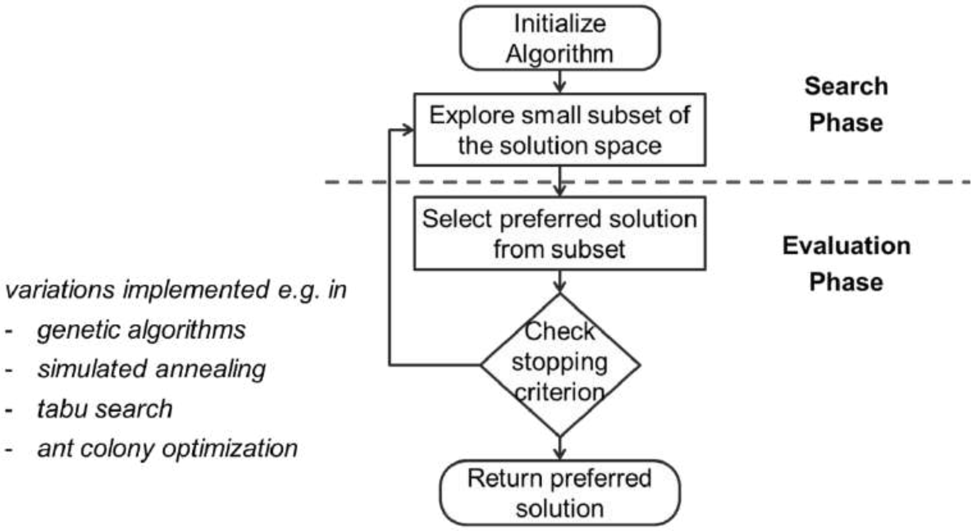

Figure 3 Basic principle of heuristic search (adapted from Fritzsche 2018)

The notion of local search results from the fact that the algorithm processes only small subsets at a time, which continuously evolve as the search advances. Due to their limited size, the algorithm can gain full transparency over the content of these sets. This makes the sets comparable to the space of knowledge discussed in C-K Theory. If the topology of the solution space was sufficiently transparent to use an analytical solution procedure in it, the entire space including its topological structure could be described as K. Since this is not the case, however, it rather has to be considered as (part of) the universe in which the space of concepts is located. What remains unclear is the actual creation and modification of concepts in the course of the algorithm.

Research Design

The argument presented in this paper follows the logic of a critical case, which provides a particularly challenging example for the scenario that is discussed. This case can then be used *a minore* to support the statement that in any other, less challenging case, the findings are even more likely to be applicable. From a design perspective, standardized industrial planning and optimization problems where genetic algorithms are used can be considered as such a critical case, because it is comparably well contained and not affected by uncertainty and openness to the same degree as most other tasks discussed in the context of design.

On the downside, this critical case is a rather unusual scenario for the application of C-K design theory. In order to find out where concepts are addressed in heuristic search procedures with genetic algorithms and similar techniques, it is first necessary to establish a framework which allows the identification of concept-related operations in the process. This is not trivial, because there are different aspects to consider at the same time.

Heuristic algorithms simplify problem solving in order to make it possible to address complicated issues in practice and cope with them in a feasible time frame. Wolpert and Macready's (1997) *No Free Lunch* theorems indicate that such simplifications must necessarily go along with a customization of the algorithms for application so certain instances of problem. If an algorithm was uniformly able to simplify the solution of a problem and yield good results, it would contradict the formal measurement of complexity measure which describes the effort necessary for problem solving using exact analytic procedures. For any given heuristic algorithm, it can therefore be proven that there are therefore problem instances on which it fails to perform well (see also Yang, 2010).

As a consequence, it is not only necessary to study the general procedural logic of an algorithm, but also its relation to a given problem instance, which results from customised settings of specific parameters which affect the way how the algorithm navigates through the solution space. For the same reason, it is also necessary to examine the way how the problem is expressed in the input information supplied to the algorithm. This concerns in particular the notion of quality. According to the definition of the problem types which are addressed, some kind of an evaluation function is required on the solution space. Without further knowledge about the solution quality which can actually available in the space, this prerequisite remains an empty statement, as it does help with the decision whether a solution is satisfactory or whether there are significant improvements which still can be reached by other elements of the solution space.

To pay respect to all these different concerns, the analysis performed on the following pages dissects the application of genetic algorithms in different stages, from the definition of the problem up to the communication of the result. The analysis is driven by the intention to identify correspondences between the application of the algorithm and the operations described in C-K Theory which go beyond mere processing of knowledge in K. these operations are:

- the generation of alternatives in transition from K to C
- the partitioning (refining, choosing, structuring) within C
- the finalization of the design in transition of C to K

Simpler said: the analysis takes all procedures under scrutiny which do not lead to a decision which is rationalized on the basis of a ruleset and calculus available in the space of knowledge.

Analysis

Problem definition

Before an algorithm can start to operate, input information about the given problem must be supplied. In this respect, algorithmic search is no different than any other project-based activity which starts with a description of the current situation and the intended changes of the situation motivating the activity. Inasmuch as industrial projects, in particular those concerned with design and innovation, are usually concerned with wicked problems, they involve vagueness and ambiguity, which are only resolved in the course of the solution process when the problem is better understood (Conklin, 2005). While heuristic search algorithms have been suggested for an algorithmic treatment of problems which are ill-defined, meaning that there is insufficient transparency for an analytic approach (Simon and Newell, 1958), the input information they receive consist of determinate values for predefined variables. If there is any kind of vagueness and ambiguity to consider, it has to be made explicit in the modelling.

Prominent sources of vagueness and ambiguity in manufacturing are temporal dynamics, e.g. regarding the order volume which is produced, the parts which are supplied, or the production schedule, which all change over time with different speed. When information is provided about factory layouts and installations as unalterable constraints in the search, temporal effects are omitted. A decision is made about one specific point of reference for innovation, which combines given knowledge about the problem situation which conceptual interpretations about those aspects of the problem with are considered as hard criteria and those which allow flexibility in the search.

The definition of the evaluation function brings up another need for decision making for which the given knowledge is usually an insufficient basis. It might be justified to assume that the digital transformation of industry yields comprehensive models of the factory which can calculate accurate information about costs, and that big data applications do the same for demand information. As already mentioned, however, this does not explain which quality can eventually be reached on the solution space. Furthermore, it can be expected that there is no perfect solution which uniformly optimizes every single aspect of quality, but only pareto-optimal solutions, which cannot be improved or a single aspect without causing deterioration for another one. Even if there is a “digital oracle” which has full information about potential improvement, innovation still involves normative decisions in setting the direction of improvements which will be pursued. These decisions are partly made explicit when the input information for the algorithm includes preference statements for certain aspects of quality (Fritzsche 2018). For the most part, however, this is left to chance, and the algorithm is designed in a way that it takes the first best solution it finds.

Search procedure

As genetic algorithms are only one out of many different heuristic techniques, the analysis of the search procedure of genetic algorithms covers only one specific case. Other techniques are much more refined and involve knowledge about the problem procedure to a higher degree that genetic algorithms. In this sense, all statements about randomness regarding the operation of genetic algorithms need further refinement to be applicable to other heuristic techniques. There is nevertheless always some degree of randomness involved in every iterated heuristic search, which make findings for genetic algorithms generally applicable to all other cases as well.

The steps for population generation and selection performed by the algorithm during each iteration show parallels to ZF set theory in terms of the underlying principles of construction, specification or refinement. However, they take place in a finite, and therefore – ignoring time constraints – enumerable set, such that concerns about choice are not necessary. In contrast to ZF set theory, a surrounding universe is existent, which makes it possible to generate new populations without further explicitly referring to axioms allowing this. As the properties of the universe remain widely unclear, the populations can nevertheless be considered to be located within an unknown environment. All the elements of the solution space which do not appear in any population remain out of scope. This can be seen as another similarity to the ZF approach in set theory, which constrains itself to those objects whose existence is granted by the given axioms and avoids universal claims as they were made e.g. by Frege.

The fact that the generation of a new population involves a large degree of random change gives reason to distinguish the search from determinate logical calculus. With Brooks (1991), the algorithm can be considered to express “intelligence without representation”. The generation of new populations is at best partially based on actual knowledge as a source of decision making, although the algorithm is likely to approximate good solutions over time. The degree to which this actually happens, however, remains undecidable in the given situation.

From the practitioner’s perspective, one can therefore say that the algorithm proceeds in the space of concepts, as there are no analytical means for solution generation involved, which are only theoretically available for the abovementioned reasons.

Algorithm customisation

Like the search procedures, the possibilities for customisation vary a lot across the different heuristic techniques. Customization is necessary because solution spaces are too big to be processed completely and there is no further information about the topology of the space in terms or quality. Depending of the frequency in which of good solutions appear in the space and their similarities, different levels of divergence and convergence in the search might be necessary.

Genetic algorithms offer the three main options for customisation (reference anonymised):

- the size of the population,
- the selection criteria determining which elements remain in the population,
- the operators which produce new elements of the population in each iteration.

Population size and selection criteria determine the memory of the process and the about of variety in the solutions which is preserved in the cause of the search. Operators determine the level of novelty produced in each iteration and the relation between old and new elements of the population. Operators increase diversity based on arbitrary choices to alter and exchange random parts of the existing element of the population. The progress which has been made before in terms of solution quality in the population is put at risk to be reversed by the operators. At the same time, the random elements in the generation of the new population can lead the search in new directions and avoid premature focus on specific kinds of solutions.

The question how the parameters for population size, selection and operator usage should be set to optimise the performance of the algorithm can only be answered with additional knowledge about the solution space. Such knowledge, however, is usually not existent when the search starts. In practice, it is usually generated by observing the performance of the algorithm under different conditions in test runs, or over a longer time of repetitive application in practice. An algorithm which is customised to perform well on a given set of problem instances is called “competent”, while knowledge about what makes the algorithm competent is acquired by the users of the algorithm (Reed et al., 2001; Goldberg, 2013). This knowledge does not directly contribute to the design process, but it creates a regulatory cycle to enable successful operation of the algorithm.

Again, the question if a certain parameter set is optimal usually remains unanswered. Potential alternative settings which yield similar results are not exhaustively explored, which makes it possible to speak about customization as another design process on an intermediate level, between the overall design of the heuristic technique and the automated execution of the search which yields the actual design artefact regarded as a digital innovation.

Search output

Without knowledge about the overall best solution that can be reached, it is impossible to say how much the elements of any given population can still be improved. The criterion to determine when the search is stopped needs to be provided from the outside. Frequently used criteria are:

1. the search process reaches a time limit,
2. no improvement has been found for a certain number of iterations,
3. the best elements of the population has reached a satisficing quality,
4. the user terminates manually for other reasons.

Setting the stopping criterion can be considered as another case of customisation. To set the criterion in a good way, knowledge about the problem is necessary. Users can acquire such knowledge over time by performing test runs and learning from different configurations, but the situation will always remain intransparent to a certain degree, such that their decision is in any case a matter of choice.

It is worth noting that the output of heuristic search does not always find acceptance in practice and that the application of the algorithm is followed by further negotiation activities (reference anonymised). Once an agreement is reached, the result can be considered to transition into the knowledge base as a reference for further search activities. All this can again be seen as a characteristic feature of design and innovation as one solution out of many which can be controversially discussed.

Discussion

Summarizing the findings of the analysis, one can say that the application of heuristic search algorithms involved the following design activities which are relevant for innovation:

1. The explication of the problem in a way that it is processable by the algorithm
   The challenge at this point is that this explication is likely to require a determination of factors which would remain indeterminate if innovation proceeded otherwise. Even without further knowledge about the solution space, the outline of the problem has to be fixed. For example, constraints have to be set in a static way or with a clear prediction of changes which may occur over time. In a team of human innovators, the perception of the problem could constantly be renegotiated, implicitly or explicitly. The algorithm enforces a decision which then serves as a basis for everything else which happens.
2. The configuration of parameters to make the algorithm "competent"
   In order to show good performance, the algorithm has to be customised to the problem situation, which involves knowledge about the correspondence between search procedure and the solution space structure with is not there. Such knowledge can only be gained by experience, based on comparisons of algorithm performance in search for solutions. Interestingly, this knowledge has a pragmatic quality: it does not say much about the solution space struc-

ture itself, but only how it should be reflected in the parameters. The parameters include the stopping criterion.

3. The actual process of search
   The search is produces the actual content of the innovation. It is performed automatically, without any further intervention by users, such that no further decisions have to be taken (interactive algorithmic exist, but remain insignificant). However, the search performance is where the effects of prior decisions become observable. What makes heuristic approaches unique is that knowledge acquisition in the course of the search is restricted to a small set of the solution space. Probabilistic arguments might allow assumption about the rest of the space, but without firm ground. The solution is generated constructively, not analytically.

In many respects heuristic search is based on a similar kind of strategy as Zermelo and Fraenkel's approach to avoid Russel's antinomy (Ebbinghaus and Peckhaus, 2007). It focusses on entities which can actively be generated by applying a well-defined set of operators. Claims about other entities are avoided. Of course, the reasons why this kind strategy was chosen are not the same. ZF set theory needed to avoid contradictions cause by universal statements, which heuristic search has to cope with intransparency of solution spaces. Constructive approaches incorporated in design and innovation, however, rather seem to be driven by the same reason as heuristic search: a general intransparency about the full range of possible results which can be achieved, whereas logical contradictions play a minor role.

Heuristic search requires the provision of information about the conditions under which it proceeds. This also has been the case in ZF set theory, since the theory was set out to describe the domain of mathematical practice, such that all elements of mathematics could be based on a solid foundation. Unlike ZF set theory, however, heuristic search cannot rely upon the structural clarity of mathematics. While digital models of manufacturing create a limited and thus widely controllable space in which solutions can be searched, it still leaves a wide space open for further normative decisions which have to be made in order to set a direction for innovation and define what improvement actually is. This leads to a situation in which design activities shift to a different level: they are not concerned with the specific innovation which results from the application off the algorithm, but rather with the general understanding of the problem situation in which this innovation as well as many others might arise, and the enablement of innovation by setting appropriate parameters for the search procedure.

One might say that the automation of the search procedure turns the attention towards the management and control of innovation, which is itself also a design process where innovation is possible. And even more than that: with respect to the problem definition, it addresses the general narrative of the enterprise as another level on which something is designed. If such narratives are also considered as innovation depends on the external environment in which they may or may not generate value.

The introduction of technical support for innovation procedures thus follows a general dynamic of systemic development. In cybernetic terms, it can be described as shift from the actual execution of certain operations to the regulatory measure which enable and ensure this execution. Speaking of this process as an industrialisation of innovation seems justified inasmuch as automation is introduced to the make the search for solutions more efficient and effective, but there is an important aspect in which this process is radically different from Taylorism and Fordism: it does not involve any claims regarding a full understanding of the process which is industrialised. Innovation does not become any more objective or rational than before. Quite in the contrary, it is very likely that the introduction of algorithms for search creates confusion in such areas as manufacturing, because it shows the limitations of logical calculus in production and operations management more clearly than before. Acceptance issues for digital innovation can therefore be expected to become an important topic, and methods to ensure the commitment of all stakeholders to the process will need to be further explored in the future.

Conclusion

Automated search procedures have the potential to contribute to innovation in manufacturing just as much as the already contribute to solutions for other complex problems in industry. The heuristic nature of the procedures is both an opportunity and a thread. On the one hand, in increased the range of applications for the algorithm to a manifold of different problems. On the other hand, the results they produce lack clarity and give easily cause for controversies. Using automated search will therefore not improve innovation in any objective way, but it can be expected to have the same effect which it already had in other fields of application: it will enable the treatment of larger and more complex structures. This might lead to an increased speed of innovation, but also to a lack of orientation.

The content of this paper is limited to a quick conceptual analysis of genetic algorithms and their relation of innovation. Other heuristic techniques have not been considered in detail and a further systematic treatment of algorithms in practical application or simulation has to follow in order to increase the rigour of the argument.

Nevertheless, there is hope that this paper can provide an important contribution to the discussion about the digital transformation of industry and innovation in manufacturing and beyond, based on cyber-physical systems and comprehensive digital models. It raises an important question for innovation management which has so far received very little attention. Heuristic search algorithms, which have so far been studied almost exclusively from an engineering perspective, are put into the context of design and innovation. Furthermore, their discussion is not limited to the actual operation of the algorithm, but is also discusses the wider scope of normative decisions which have to be made regarding the problem definition, customisation of the search and utilisation of the results. The paper builds a bridge between research on the digital transformation in innovation management and research on algorithms in operations management which inspires further work in this context.

At the same time, the author hopes that this paper is also informative for researchers concerned with C-K Theory by approaching the theory from an unusual perspective. In particular, it addresses an application scenario from industry where formal logical and set-theoretical arguments seem replaceable by more practical, complexity-oriented arguments regarding intransparency and missing knowledge. Parts of these arguments are very strongly reminiscent of intuitionist ideas in mathematics. However, the practical background on which they are expressed brings in another aspect as well which might be relevant treatments of innovation from a design perspective, too.

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