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A SYSTEMATIC APPROACH OF DESIGN THEORIES USING GENERATIVENESS AND ROBUSTNESS

Armand Hatchuel[1], Pascal Le Masson[1], Yoram Reich[2], Benoit Weil[1]
(1) Mines ParisTech (2) Tel Aviv University

ABSTRACT

In this paper we build a systematic comparison of several formal design theories: General Design Theory, Axiomatic Design, Coupled Design Process, Infused Design and C-K theory. Each theory offers principles as well as mathematical assumptions and establishes propositions that we analyze through two main criteria: i) their generativeness, i.e. their ability to produce design proposals that are different from existing solutions and design standards; ii) their robustness, i.e. their ability to produce designs that resist variations of context. Using such framework, and focusing on the evolution of the mathematical assumptions of each theory, it can be shown that the development of design theories does not reflect radically different point of views about design. Instead, there is an evolution towards more generality and less dependency on predefined objects. They form altogether a consistent body of knowledge that has aimed to increase the generativeness of design without losing its robustness. Thus, Design science can be seen as the science of "generativity". The evolution of design theories is illustrated by applying each of them to the same brief: the design of a new camping chair.

Keywords: Design theory, comparative methodology, generativeness, robustness

INTRODUCTION

During the last decades, there has been an active renewal of formal design theories. Since the development of Yoshikawa's General Design Theory (GDT), Suh's Axiomatic Design (AD) has appeared as well as Reich and Shai' Infused Design (ID), Braha & Reich's Coupled Design Process (CDP) and Hatchuel & Weil's Concept-Knowledge theory (C-K). Such multiplication of theoretical proposals calls for comparative studies and, hopefully, to new synthesis on the present state of Design science. Thus, from an academic point of view it is important to check if these different models are mutually consistent and if they could form an integrated body of knowledge that we can call "design science" [1]. In many sciences, it is a constant aim to avoid contradictory theories or to explain why there may exist different, *yet equally valid*, perspectives (for instance, Euclidean and non Euclidean geometries). Most often new theories claim to be a generalization and an extension of previous ones. Hence, it becomes a major issue to identify how such generalization is interpreted and if it is consistently elaborated. For instance, in modern Physics, Einstein's special relativity extends Newtonian's mechanic by generalizing the definition of time to a moving referential, yet both theories are consistent for ordinary values of the referential's speed. Likewise, the field of design science would be clearly strengthened if a rigorous articulation of design theories could be established. *So, what could be a general logic of design theories?* Does it exist at least for the *formal theories* of design? Such investigation needs to better understand specificities and complementarities between these different theoretical propositions. This paper aims to establish first elements of such program.

METHOD – COMPARISON FRAMEWORK AND SAMPLE

Large literature reviews have been done on design methods and design philosophies [2]. They describe different intuitive and broad perspectives on design (descriptive models, prescriptive models, computer based models, etc.). Formal design theories allow for *a tighter* and more systematic comparative approach. The assumptions, objectives and mathematical models specific to each design theory can be more easily mapped one to the others. Such approach has already been applied to one-to-one comparison studies (i.e., GDT vs. CDP by [3]; C-K vs. CDP by [4]). In these comparisons, the newer theory shed new light on some theoretical assumptions of the previous one. These first findings pave the way to more general comparisons, which could hopefully reveal deep scientific evolutions and stimulate advanced perspectives on design theory.

Generativeness and robustness of design theories: definitions and hypotheses

A comprehensive framework encompassing all available formal design theories is still an open research issue. However, in this paper we propose two steps towards this end.

First step: we comparatively review the central principles of each design theory; focusing on how *design is defined* and on the mathematical assumptions that are used to model the *knowledge background* and *context of the designer.* These elements are necessary for the second step of comparison.

Second step: we compare design theories through two performance dimensions that we call: *generativeness and robustness*. These notions generalize two well known series of design criteria that are traditionally discussed in the literature (see the introduction of [5]). On one hand, design is needed when no standard or straightforward solution exists and new artefacts have to be "*generated*"; on the other hand, design has to be *robust*, i.e., reliable, realizable and feasible, both from the designer and the user point of views. These two series of criteria can be generalized under the following definitions.

Definitions

a) We define *generativeness* as the capacity of a design theory to produce "novel" solutions (see for instance [6]). From a formal point of view, this needs to identify how each design theory builds: i) its own *knowledge background* (existing knowledge, object definitions, learning capacities, etc.); ii) its *design process*: the operations, steps, decisions, and evaluations that guide the construction of one or several solutions or design outputs. Intuitively, *the mo*re the knowledge background of design is fixed, the less novelty will be accessible to a design theory. However, the fruitful use of optimization heuristics in design seems to temper this intuition and needs a special comment.

Comment: Optimization needs, by definition a fixed background of possible solutions; thus, what is the generativeness of classic optimizing algorithms (say simplex, branch & bound, genetic algorithms and others)? These algorithms aim to find an "optimized" solution among a large number of well defined candidates (admissible solutions). According to our definition, the generativeness of such methods should be *zero*, as all candidate solutions are mathematically established *a priori*. However, it is well known that when dealing with NP-complete problems the set of candidate solutions cannot be completely enumerated within an acceptable time and special heuristics are needed. Such procedures *seem to possess a generative power* as they may help the designer reach "surprising" and unexpected solutions. Yet in absolute terms, these findings are still pure combinations of existing solutions and no true novel solution can appear from a fixed set of possibilities. Thus, from a formal point of view, it is more appropriate to say that optimization techniques offer a *search power that may trigger generativity if the designer is inspired by unexpected findings. But, optimization is not generative in itself.* Compared to an optimization situation, a design situation is *generative* because *not all candidate solutions could have been defined*, and not only non-enumerated, from the beginning. A technical consequence of this distinction will appear in later sections as design theories had to model generativity with expansion processes that go beyond searching in a fixed set of solutions. Thus, classical optimization techniques keep all their value as a component of the design process but they cannot describe its essence.

b)We define *robustness* as the capacity of a design theory to help the designer reach a robust design. A design is said to be *robust* when it produces *expected performances* despite being subjected to uncertainties or hard-to-control disturbances (often called "noise factors") [7]. For instance, Taguchi's method aims at being robust to changes in manufacturing parameters or external conditions [8, 9]. More generally, robustness has different dimensions according to the type of disturbances that are considered including changing customers (or customers' needs, uses, etc.) or changing design conditions (e.g., functions or parameters). Our definition of robustness focuses on product robustness. Process robustness may be included if it impacts product robustness.

Remark: in this paper, we claim no *absolute* measure of generativeness and robustness and we only study and compare how "generativeness" and "robustness" are modeled in each design theory.

Sampled theories and illustration example

Sampled theories: This study is limited to Design theories that are grounded on formal models. By *formal model* we mean the formulation of a set of axioms and *proven* propositions in such axiomatic context. We selected five theories for our study: Yoshikawa & Tomiyama's General Design Theory

(GDT), Suh's Axiomatic Design, Braha & Reich's Coupled Design Process (CDP), Shai & Reich's Infused Design (ID), and Hatchuel & Weil's Concept-Knowledge theory (C-K theory). The mathematical grounding of these theories is different but all aim to reach a clear *axiomatization of design* and *to prove their findings*. Other theories could have been reviewed [10, 11] but we had to limit our list in this paper.[1]

Illustration example: After giving a short comparative account of each theory, we illustrate their principles and methods by a *simulated* exercise. We have tried to find examples of designs that a designer would produce if he followed the principles of each theory to answer the following brief: *design a new camping chair that would be easier to pack and install, lighter and as comfortable as existing camping chairs*.

Hypotheses and research issues

Based on these definitions, we can formulate three hypotheses, H1, H2 and H3 that we expect to confirm or refine through our comparative study.

- **H1**: Design theories can be distinguished from other *models of thought* [14] by their specific focus on generativeness;
- **H2**: The evolution of design theories can be interpreted as extension logic where new theories attempt to *increase their generative power* while maintaining at least the robustness of previous theories.
- **H3**: The increase in generativeness requires mathematical models that are less and less dependent of the structure of objects that are designed.

PART 1. GENERATIVENESS AND ROBUSTNESS OF DESIGN THEORIES

We describe the generativeness and robustness of several design theories and summarize it in Table 1.

Table 1: Summary of the comparison between design theories

Theory	Year introduced	Mathematical model	Generativeness	Robustness
GDT	1981	Entity set as a Hausdorff space; topology of function- attributes laws.	Fixed entity sets and combinatorial generation; no articulated mechanisms for K expansion.	Search in topological proximity. Process robustness guaranteed by reusing existing designs. Product robustness depends on topology.
AD	1988	Matrix algebra between functions and attributes spaces; control theory; information theory.	Robustness-driven design improvements; Indifferent to K expansion.	Axiomatically defined by decoupling and minimum information.
CDP	2001	Coupled attribute-function space; coupled transitions defined as closure operations.	Coupled Dynamics between functions and parameters; permits K expansion, no mechanism articulated.	Adaptation to changes within topological structures depending on available knowledge.
ID	2001	Duality and other theorems between system models, which are discrete representations (e.g., graphs, matroids).	"Local" K expansion by detecting gaps stimulates new designs.	Process robustness guaranteed by knowledge structures. Product robustness depends on available knowledge in multiple disciplines.
C-K	2003	Logic and Modern set theory; model extensions.	Mechanisms for K expansion through concept expansion; emergence of new objects or revision of objects definition.	Functional and parametric flexibility; search a close C branch or use related K if design needs to be adapted.

General design theory: a combinatorial approach of design

Principles and knowledge background

GDT is based on a large number of axioms and principles. However, the main notion of GDT (see [15-18]) is its definition of entity sets. An entity set S is defined as *the set of all real objects that existed, exist and will exist (e.g., the set of chairs)*. Then entities are described through subsets of S (called abstract concepts) that are either *attributes* (a property that can be observed or measured) or *functions* (a behavior that is displayed by the entity in a certain situation).

[1] It is important to mention that there are design theories that do not use formal models. For this reason the classic German systematic approach is not part of this analysis, even if it plays a central role in the design tradition and some authors have begun to analyze its historical, formal roots [12, 13].

The background knowledge of GDT is defined as a topology over *S*. GDT distinguishes between "Ideal knowledge" and "Real knowledge". In the first case, the topology is such that a designer *"knows all the entities and can describe each of them … without ambiguity*" (quoted from [14]). This translates to proving that the entity set is a Hausdorff space. This may require an infinite set of abstract concepts. In such case, designing means simply *choosing an entity* in a catalogue based on functions. In the case of "Real knowledge": there is a topology, where entities can only be described by a limited number of *attributes* and by *models linking a function to its related attributes.* In this case, design becomes the search for the best fit between a group of functions and a group of attributes (see fig 1). To illustrate GDT let's take an example [15]. The entity set contains *k* seats, for each seat there are attributes and functions. A designer begins to create a new chair with some of the attributes and functions. Based on models linking each function (e.g., esthetic) to one or more attributes (e.g., visual aspect), she progressively selects one subset of the entities that possess all required functions except one. And finally, using one last model for the missing function she adds one attribute (add a brake) which creates a chair different from the *k* existing ones. In the logic of GDT, this chair is "new", yet it is only the identification of a chair of the entity set (which also contains all objects that will exist). Formally, the feasibility of this "new" entity is warranted by the structure of *K* i.e., the topology of models in *S*.

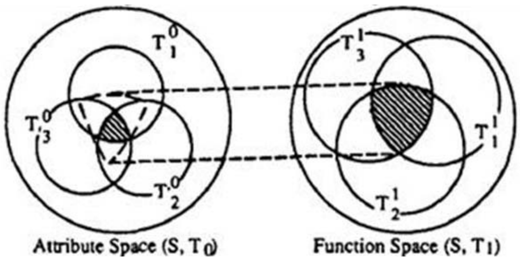

Figure 1: GDT: Design as the best fit between set of functions and set of attributes

Generativeness and Robustness

The formal complexity of GDT is mainly a warrant of the good behavior of the entity set, while its design method is purely combinatorial. Design uses existing entities or building blocks similar to "machine elements": the models that link a function $\boldsymbol{f_i}$ to the attribute $\boldsymbol{a_j}$. The generative power of GDT is fixed by the entity set and by its topology; hence, it is limited by the list of abstract concepts (attributes, functions) assumed to be known in advance. Finally, within GDT, design is obtained *by a combination of known and compatible attributes and functions* while any of them belongs to at least one entity of the entity set. The robustness of the design depends on the structure of the entity set.

Axiomatic Design: robustness as a driver of generativeness

Principles and knowledge background

As in GDT, AD defines design as a mapping between design parameters (DPs) and functional requirements (FRs). However, AD does not describe how such mapping is built and leaves it to existing design theories like GDT. AD is at first glance a *theory of design robustness* [19-21]. Within AD, a design is ideal if it is robust from the points of view of the designer and the user and both points of view are axiomatically defined. The main mathematical models of AD are i) the interpretation of a design as a matrix algebra between DPs and FRs; ii) a theory of the quantity of information involved by the adjustment of the FRs. AD is clearly related to control and information theories.

-AD's first axiom, called independence axiom, corresponds to the designer's robustness. It states that a design should be *decoupled*, i.e., it should install a one-to-one correspondence between DPs and FRs (diagonal or Jordan-block DP-FRs matrix) (see fig 2). Such decoupling warrants that a variation of one DP or one FR will not destabilize the whole solution.

- AD's second axiom corresponds to the user's robustness. It states that a decoupled design should also follow the principle of minimum information for the user. This means that the user should not have to adjust any design parameter in order to benefit from the functions of the system. In AD, the "user" may be seen either as the production engineer that needs simple and reliable manufacturing, or as the consumer that expects an easy utilization of the product.

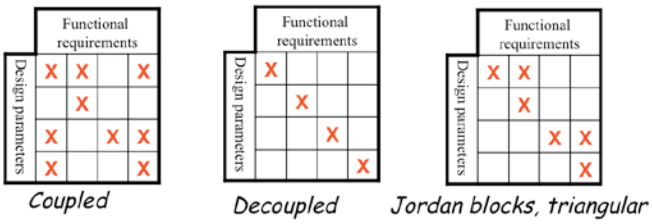

Figure 2: simplified representation of the first axiom

Generativeness and Robustness

Clearly, AD builds a normative definition of robustness, which is not presented in any other formal theory but it is compatible with all of them. The generativeness of AD is not spelled out in the structure of the theory. However, it is clearly claimed as a consequence of the axiomatic quest for robustness. To follow the axioms of AD, designers will have to look for new DP's and new FR's that decouple the matrix and minimize the user's information. Thus, they will design a new system that corresponds to an extended DPs-FRs Matrix. Finally in AD generativeness begins after some design has already been built. However, the knowledge background of AD and its possible evolution are not specified.

Coupled Design Process (CDP): bringing functional flexibility to GDT

Principles and knowledge background

CDP can be considered as a direct generalization of GDT that increases design generativeness [3]. Instead of a fixed entity set defined as a topological space in GDT, CDP only assumes that design is a process in which functions and design parameters (the "attributes" in the language of GDT) co-evolve. There is no static fit between a fixed list of functions and attributes. Instead CDP models the topology of series of coupled changes $(f_i, d_i) \rightarrow (f_j, d_j)$ where new functions and new attributes can be added in order to account for new problems and new design conditions. These transitions are modeled as operations in a coupled closure space, which is more general than a Hausdorff space. This coupling means that the designer may indifferently start from functions and find attributes and the other way round. Thus, CDP includes learning and discovery as an integral part of the design process.

Generativeness and Robustness

Braha and Reich have shown that GDT is a special case of CDP; consequently, CDP allows a stronger generativeness than GDT [3]. Similarly, CDP is as robust as GDT. Moreover, in design situations outside the scope of GDT, CDP robustness relies on the dynamic structure of its knowledge as well as the description of the design process as a progression in a closure space. This progression provides functional and attribute flexibilities as well as a trace that could be reused to generate designs adapted to new situations. The generativeness of CDP is more powerful that in AD because it is built in the design process itself and the knowledge background of AD is not specified. As far as robustness is concerned, AD can be used in CDP as guidance to refinement and synthesis operations.

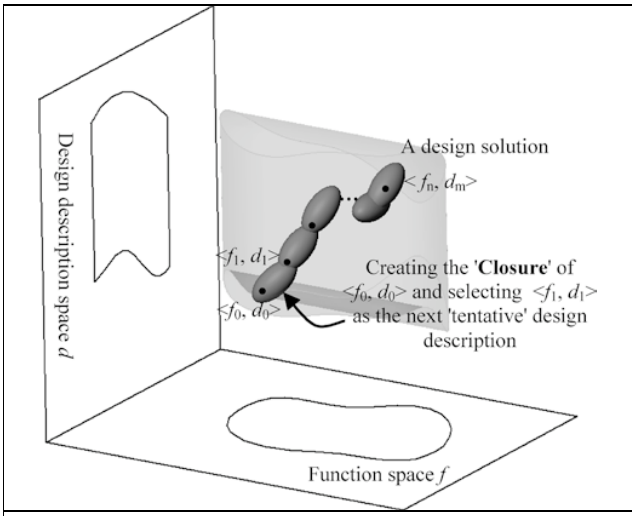

Figure 3: CDP: dual refinement of functions and design description (source: [3])

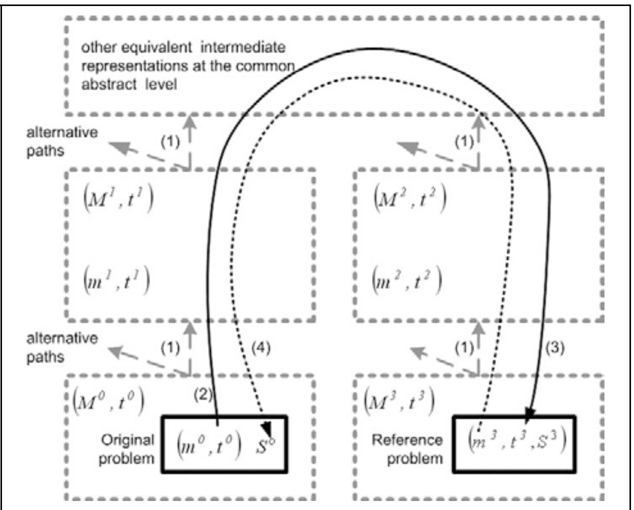

Figure 4: ID: abstract model of the method (source: [22])

Infused Design: Generativeness through Knowledge dualities

Principles and knowledge background

ID [22-24] keeps the functions-attributes model of design. But, compared to the preceding theories, ID introduces formally the impact of *the transformations of the knowledge background in the design process*. Such dynamics was absent in GDT and only implicit in CDP and AD. Moreover, ID specifies a special class of knowledge transformations that is of direct help for the designer. These transformations build on mathematical relationships that exist between several fields of engineering science such as duality, generality or equivalence (for instance, between trusses and mechanisms). Thanks to these mathematical relationships, a design problem that is formulated in the language of one field can be rigorously translated in the other field where it can be solved more easily, and finally the design solution is reached by the reverse translation.

Generativeness and Robustness

Generativeness is the major aim of ID. The structure of knowledge is a mediator between functions – problem definition – and attributes – solutions (whole or parts) available in other fields. While ID could lead to innovative solutions in one field, it in fact, only reuses parts of existing solutions. The generative power of ID comes from connecting knowledge sources that previously where perceived to be distinct and through ID become part of a single piece of knowledge. Metaphorically, ID serves to extend the topological space available to designers in the framework of CPD or other theories. Robustness in its classic interpretation is built into ID through the mathematical foundation that warrants the validity of the solutions translated from another field. The robustness of these solutions is as the robustness of the reused solutions.

Concept-Knowledge theory (C-K theory): generativeness through dual expansion

Principles and knowledge background

C-K theory differs from GDT and AD by first abandoning the definition of design as a mapping between functions and attributes [4, 25, 26]. Instead, design is defined by the formulation of a “concept”: a proposition that states the existence of an object O having some properties P_i (and like in CDP, these P_i can be said indifferently attributes or functions). Moreover, within C-K theory, it is shown that design requires that such concept is undecidable within the knowledge background that is available to the designer. Thus, the object O appears as both *unknown and desired* for the properties P_i that the designer should reach. Such definition of design implies that, like in ID, the designer cannot reach a proposition without expanding its knowledge. And the core operations of C-K theory explain how this knowledge expansion is interactively built with the expansion of the space of concepts, i.e., the different “design paths” that are followed by the designer. A central finding of C-K theory is that a design solution can be reached only if the definition of some object (or entity) of the knowledge background is *revised* (expanding partition). This means in practice the emergence of new categories (new names) and new connections between different knowledge domains.

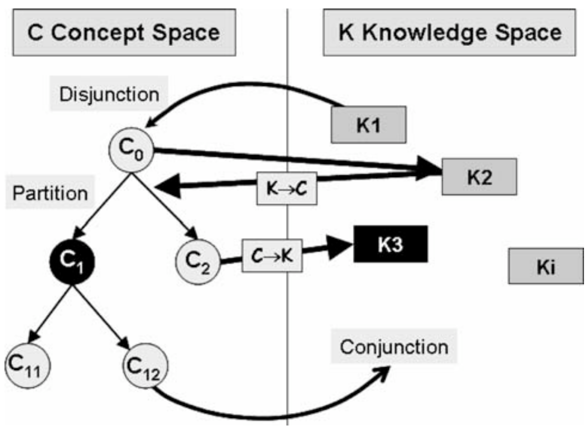

Figure 5: Dual expansion of Concepts and Knowledge in C-K theory

Mathematically C-K theory assumes that concept and knowledge spaces can be described with modern set theory and with standard (and non-standard) propositional logic[27]. Basic findings in Set theory like the independence of the axiom of choice are needed to model the special status of concepts. The design of a new object is seen as an equivalent to the “forcing” operation that builds new models of sets by *generic extensions* [25]. Yet, in C-K theory the existence of a design solution requires necessarily some knowledge expansion.

Generativeness and Robustness

C-K theory generalizes two relativistic perspectives on design: i) like in ID, design is always relative to the knowledge available or accessible during the design process; ii) like in CDP, functions are no more a fxed set and are dependent of object definitions that could be revised by new knowledge. These perspectives increase one step further the generativeness of design: new objects and new knowledge must emerge from the design process. Moreover, two aspects of generativeness are disentangled: in C, the capacity to reach the larger *variety of solutions* and the most surprising ones; in K the different domains where knowledge has been increased. However, in contexts where knowledge is fixed and all entities are well defined, C-K theory will be identical to GDT (there are no more concepts and design becomes combinatorial programming). Concerning robustness, C-K theory models the family of C branches that correspond to a common and close area of K: this allows finding near equivalent designs in case of context changes.

PART 2. ILLUSTRATING DESIGN THEORIES: VARIATIONS ABOUT CAMPING CHAIRS

Illustration rules: The goal of this exercise is to illustrate the different principles of each design theory when they are applied to the *same* design brief. Variations in the resulting designs will also give examples about what we meant by the generativeness and robustness expected from each theory. The design of a new camping chair was selected for reasons of simplicity and because the knowledge background of such design (chairs, backpacks, camping situations…) is largely shared. The brief is to design a *new camping chair* that is expected to be i) easy to transport and pack; ii) as light as possible; and iii) comfortable. In order to reach some reality in this exercise, we did not designed the new camping chairs ourselves but selected in the existing market those camping chairs that seem *to best fit the principles of each design theory*. In doing so, we also do not present a systematic development of the design brief through the principles of the theory to justify the selection of the solution for each particular theory. This would require doubling the size of the paper and would still not serve as a good test. We acknowledge that these choices are the result our own understanding of the theories. It would have been more rigorous to build an experiment where independent groups of designers would answer the same brief after being trained in one specific design theory. However, in this paper, we use this exercise not as a test of each theory or of our claim but only as an illustration of our conceptual comparisons. To our knowledge, there has been no similar attempt in the literature, in spite of the potential value of such comparative illustrations for the teaching of design theories [28].

Camping chairs designed by GDT

The principle of GDT is first to establish the set *S* of existing chairs. The targeted camping chairs are thus subsets of *S*, i.e., chairs that present the properties formulated by the brief. Obviously, we will find a set of chairs that are very light, a set of chairs that can be disassembled or foldable etc.; thus, the logic of GDT will be to intersect these sets and pick one of the chairs in the intersection. The method is simple and obviously robust as it uses the long legacy of chair design and as any existing function can be added to a solution (by intersecting the previous result with the set of hairs with that function) and yet generate a viable chair in most cases. Thus, it is not surprising to find that the most common camping chairs on the market (see fig 6) would probably be the result of a perfect student of GDT.

Camping chairs designed by Axiomatic design

As mentioned earlier, AD triggers generativeness by guiding an increase of design robustness. This means that the departure point of AD is a classic camping chair that will be improved through AD's principles. If one looks at classic camping chairs, one remarks that the attributes that impact weight and packing ability tend to limit the comfort of the chair. That is, the system is a coupled design. The first axiom would invite us to find some independence between functions and attributes by modifying the attributes. Thus, one suggestion would be to look for a more *cosy* textile structure that has small impact on other functions. We did not find many camping chairs that clearly obey AD principles but the chair-seat in fig 8 corresponds to a more decoupled Suh's matrix and from the point of view of the user, it is certainly easier and more comfortable to seat in it.

Camping chairs designed by CDP.
In CDP, the design logic is less static and no more purely combinatorial. There is no fixed entity set. Thus, camping chairs *are not necessarily subsets of the set of chairs*. The functions and attributes of a camping chair can change dynamically. An example of such functional dynamics can be found in the exploration of the camping situation. If a camping chair has to be light and comfortable, this can be also reached by giving to the chair some extra functions that will contribute to a lighter camping pack. Hence, a design by CDP will extend GDT-type solutions with new functions that emerge from the design process itself. It will also explore situations where attributes become functions and conversely. In fig 7, we give examples of such designs where camping chairs are also camping tables or walking sticks or even the backpack itself! One can ask if GDT would not find such combinations. The answer is yes, but only if the structure of the entity set of was treated not as a fixed base but as a changing set during the design process. This remark shows the increase of generativeness that is afforded by CDP; also, it confirms the consistency between these two design theories.

		
Figure 6: Standard camping chairs as illustration of GDT principles	*Figure 7: Camping chair as illustration of AD*	*Figure 8: Camping chairs as illustrations of CDP*

Camping chairs designed by Infused Design
The principle of infused design is to transform the knowledge used by the designer from one field to another. All preceding camping chairs were designed as simple mechanical structures. ID would suggest to look for designs that could be obtained for instance by tensile structures or fluid mechanics. This transformation of the knowledge background obviously will change all classic attributes of chairs, and new functions may be necessary. Fig 9 (right side) shows chairs that are close to such ID logic. We can remark that there are no more “legs” and that the floor is part of the “chair” and that the weight of the body contributes to the stability of the chair. However, a more interesting approach (yet, not in the market) directly using ID-driven research, could be based on a foldable tensegrity structure (see fig 9 left side [30]) that could be configured by the user to provide sitting and back support adjustable to desired positions and body sizes and weights. As mentioned before, AD could be applied here to modify the flat triangle platform into a cozy textile structure that improves comfort by decoupling the comfort and stability/packing functions.

Camping chairs designed by C-K theory
In C-K theory, we know that design is the result of a dual expansion in the concept space and in the knowledge space. The role of the concept space is to structure the different design paths according to the available knowledge or to remark that some designs paths point out in directions where knowledge is missing. The different designs obtained by GDT, CDP and ID clearly would appear as partitions in C obtained by different knowledge about *supporting structures*. Thus, a complementary undecidable concept would be generated in C: “a camping chair which has no supporting structure”. The concept is surprising but it shows the generativeness of C-K theory. The problem is now to look for new knowledge that would help to find new partitions (i.e., attributes or functions) of such strange concept. If there is no supporting structure, this means that the person is sitting on the ground or on a simple mattress. But sitting on the floor is not at all comfortable, except if we design something that makes it comfortable! As expected, the logic of C-K will guide us to a revision: *we can now think of a camping chair that makes sitting on the floor quite comfortable*! Well, such “camping chair” really exists on the market and can be seen in Fig 10[2]. It has even won a design award! One can doubt of the comfort of

[2] In ICED 2003, Hatchuel and Weil made the first presentation of C-K theory with the example of the “camping chair that is not a chair”. At that time, the belt-chair was sold in France by Sport shops. Such belt can be seen in a video entitled “designing

such chair but users are positively surprised and some reflexivity about what we know about comfort is thus stimulated. This is not the only design that would emerge from C-K theory but this example shows the generative power reached by design theory: clearly, design *can be rigorously modeled* without being dependant on existing definitions of objects (like chairs) and functions (comfort). What matters is the interaction between the expansion of design orientations and knowledge transformations.

Figure 9: Camping chairs as illustrations of ID

Figure 10: Camping chair as illustration of C-K

MAIN RESULTS AND DISCUSSION

The logic of design theories

To synthesize the main results of this comparative analysis of design theories we can now return to the discussion of the three hypotheses that were formulated in the introduction of this paper.

***H1**: Design theories can be distinguished from other models of thought [14] by their focus on generativeness.* Like Decision theory, optimization theory and Artificial intelligence, Design theories are models of reasoning, or "models of thought" as Herbert Simon's coined them. This does not mean that design is a pure mental activity, but that in design all aspects of human activity are mobilized towards a specific rationale and for some specific intent and meaning. It is usual to say that the intent and meaning of design is to solve problems or to fulfill some needs. But these tasks are not specific of design activities [29]. And we need to add that the design rationale is both to: i) *generate* objects *that didn't exist before*; and ii) *warrant* as much as possible their existence. Yet, "generation" is not a phenomenon that is easy to model and all design theories had to explore it. The simplest way was to think of generation as a *combination* of existing objects or elements, likewise language generates new texts by combining invariant signs or letters. But the realm of design has no limits and what is valid for phrases and texts is not valid for materials, machines, sounds, etc. Therefore, design theories had to think beyond pure combinatorial processes and explore different *forms of generativeness*: dynamic transformations, adaptations, hybridizations, as well as discovery and renewal of objects. GDT is clearly at the *frontier between combinatorial/optimization theories and design theories,* it is a combinatorial theory yet its generativeness is apparent even if in a simplified and limited form. After GDT, all other theories will depart from the combinatorial/ optimization logic and clearly focus on generativeness; it is even the case of AD, which appears first as a robustness theory but claims its generative power.

***H2**: The evolution of design theories can be interpreted as an attempt to increase their generative power without endangering their robustness*. Our study clearly supports the proposition that formal design theories evolved towards a greater generative power. Both the comparison of conceptual models and the illustrative designs support this finding. From GDT to C-K theory, the focus on generativeness has become the core mechanism of the theory. This trend is also observed in the study of the German sources of systematic design theory in an historical perspective in [30]. There are practical reasons for

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the unknown. 25 mn" at the web site Vimeo (http://vimeo.com/11556338). Since then, a famous design company has launched it again and call it "Chairless".

this search of more generativeness. The increase of R&D efforts in industry necessarily calls for more innovative designs [31]. It also reduces the value of design processes that would be independent from *research processes*. Excepting GDT, all other design theories are related in some way to research and knowledge expansion. And generativeness departs interestingly from a pure combination of existing components because it includes research that changes the components available for a solution. Yet, generativeness cannot be reduced to pure research as the knowledge expansion is *directly guided* by the design process. In the evolution of design theories, robustness is not forgotten. It is more and more clearly associated with the knowledge structure. In GDT, robustness is embedded in the topology of the entity set. If such topology was valid, all other theories would have the same robustness as GDT. When such entity set no more exists, robustness is dependent of the structure of Knowledge. Moreover, when a new dimension of robustness is introduced (like in AD and ID) it can be applied to the preceding theories. The increase of the generative power of design theories is also a pure scientific challenge, as generativeness needs special mathematical assumptions (see below).

***H3**: The increase in generativeness requires mathematical models that are less and less dependent of the structure of objects that are designed.* Intuitively, the more a design theory is dependent of rigid structures, functions and parametric definitions, the less it is generative. Therefore, design theories tended to build on more general and relativistic topologies and models. In GDT, the topology of the entity set is very strong and aims to build a world of very well defined and distinguishable entities. In such world, new objects are possible but if they maintain the overall existing structure and definition of entities. In AD, the capture of a design through a Suh's requires specific assumptions about functions and attributes (for instance, the independence between the definition of functions; otherwise, all designs are necessarily coupled). Such assumptions are c*learly valid when the designed objects belong to a well established engineering and scientific field*. With ID, the transformation of the knowledge of the designer is introduced. The mathematical tools used are duality and other theorems that transform an engineering field into another. Thus, designers use meta-structures of knowledge: deep mathematical structures common to different engineering fields. Knowledge is not only about functions and attributes; it is about the basic properties of object modeling. In CDP, we find "closure operations" which allow going from a function to another function. Closure operations are very general properties of Sets built on topological spaces. This means that the designer can now work with a great variety of objects properties and that the background of design theory reduces to general structures like modern set theory. C-K theory adds to this background the explicit regeneration of existing sets of objects. Thus, the mathematics of C-K do not only use classic Set properties but also properties of the axioms of set theory like Independence theorems which show (a major finding of set theory) that we can rigorously work on unknown objects. The designer is thus allowed to work on "imaginary" objects without creating nonsense: invention is now integrated in the logic of design. Finally, design theory becomes sufficiently general to be valid outside the stable world of standard physical objects. We can think rigorously of the design of any "new object" with only minimal requirements on the logic and structure of the knowledge about such objects. Further research should explore if unique mathematical description of all Design theories clarifying the assumptions that deduce each of them from this unique set of axioms.

Generativity vs. creativity: design as a science of generativity

As expected, a comparative study of design theories offers a deeper view about what Design science is or at least will be. If all sciences have to warrant their propositions by some "reality" tests, then all sciences face a robustness issue. Hence, robustness is vital for design science but it cannot distinguish it from other sciences. *It is therefore a natural conclusion of our investigation that the specific object of design science is "generativity".* At this point, it is obvious that the notion of generativity seems close to the notion of creativity and there is a wide literature that studies the links between design and creativity. It is not possible to review here the findings of this literature. However, our research opens a question that will be explored more systematically in further research.

From a historical point of view, Design Science has been different from the science of creativity. The first one has its roots in the fields of architecture and engineering, the second one in the psychological tradition. The progress of design theories clearly supports the proposition that a science of generativity is emerging, departing from the classic combinatorial/optimization tradition and deepening its mathematical underpinnings in other sources [26, 27, 32]. In spite of their common aspects, Generativity deeply differs from creativity. Creativity is usually defined as a "natural" capacity of the mind to produce novel ideas. Instead, the evolution of design theories establishes that generativity can be seen as a *systematic model of thought that both creates new objects with desired properties (not only free ideas) and provides the new knowledge necessary to warrant their existence*. Meanwhile, creativity is now approached through more cognitive perspectives [33-35]. It is very likely that both evolutions will contribute to new perspectives on the relations between generativity and creativity.

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Armand Hatchuel
MINES Paris Tech, Center for Management Science, Chair of Design theory and methods for innovation
60 Boulevard Saint Michel, 75 272 Paris cedex 06, France
Tel: +33 1 40 51 91 09
Fax: +33 1 40 51 90 65
Email: hatchuel@ensmp.fr

Armand Hatchuel is Full Professor and coordinator of the Chair of Design Theory and Methods for Innovation at MINES ParisTech. He is the co-chair of the design theory special interest group of the design Society. Area editor for Research in Engineering Design, he is a member of the French National Academy of Technologies.

Pascal Le Masson is Professor of the Chair of Design Theory and Methods for Innovation at MINES ParisTech. He is the co-head of the engineering design and innovation teaching program at MINES ParisTech.

Yoram Reich is a processor at the Faculty of Engineering, Tel Aviv University. He is the Editor-in-Chief of *Research in Engineering Design* and serves on the editorial board of 5 other journals; a co-chair of the design theory special interest group of the design society, and a member of the advisory board of the society. He recently founded and is the chairman of Israel Institute for Innovation Technology

Benoit Weil is Professor and coordinator of the Chair of Design Theory and Methods for Innovation at MINES ParisTech. He is the co-head of the engineering design and innovation teaching program at MINES ParisTech.