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ABSTRACT

The CK theory of design created by Hatchuel and Weil has raised interest and controversies both in the academic community and among practitioners.

After presenting the scope and focus of CK theory, and the contributions claimed for it by its creators, we compare it to concepts and models more commonly used in traditional design approaches. It can be noticed that important concepts are ignored by CK theory, even if some of them are integrated into the research programs of Hatchuel, Weil, and Le Masson. This initial analysis demonstrates that even in its scope, CK theory appears incomplete for engineering design and does not consider important dimensions of the validity of the research program as claimed.

Then we analyze the foundations and hypotheses of CK theory from a critical viewpoint. Some suggestions for its improvement are made. Additionally, the ability of CK theory both to effectively assist and direct the creative process and, moreover, to organize the complete design and innovation processes is questioned.

Finally, we draw conclusions about the ambitious program and results claimed by the creators of CK theory.

1 INTRODUCTION

During the past two decades, the growing economic problems faced by traditional industries in Europe and the USA have been seen as a result of the emergence of new economic powers, mainly located in Asia. This evolution has emphasized the importance of innovations as a key parameter for the survival and renewal of industry in these areas much more than was previously the case.

At the same time research, initiated by S. Kline and N. Rosenberg in their *Chain*-Linked *Model* (1986), has shown that in order to improve the ability to innovate, we must take the design process into account. This hypothesis gradually led to the development of design theories that were able to explain and direct innovation processes and strategies. CK theory is one of the attempts to address this challenging scientific issue. The present article aims at analyzing this theory and is organized in the following manner.

First, we present the scope and focus of CK theory.

Second, we develop a comparative study of the concepts used in CK theory and some existing concepts and tools that have been developed before in design science. This parts shows that CK theory is not trying to integrate most of the existing concepts but instead to develop a different approach that has a great deal in common with inferential design theory. Several concepts used in CK theory have been previously introduced in the inferential theory of learning and in inferential design theory, where the concept of concept and knowledge are both used.

Third, we develop a critical analysis of CK theory, showing that its real operability scope in the design context is probably limited compared to the claims made by the creators of the theory. In the last section, the paper draws conclusions about the new developments provided by the theory and also summarizes the limitations highlighted by the authors of this article compared with the claims of the creators of CK theory.

2 A SURVEY OF CK THEORY AND ITS CLAIMS

The present section aims at presenting the key concepts of CK theory. Before presenting them, it is, however, necessary to understand the purpose and scope of such a theory.

2.1 Purpose and scope of CK theory:

Le Masson, Weil, and Hatchuel position their work in the RID model, where R stands for Research, I for Innovation, and D for Development [2].

According to them, D is defined as a controlled process which activates existing competences and knowledge in order to specify an artefact which should satisfy some well-known objectives. From such a viewpoint, the development process aims at instantiating parameters, these parameters being fixed ex ante by a generative model. Thus, the extent to which D can support the exploration of new alternatives is not independent of the generative model on which the development process is based.

Research is defined as a process which provides the scientifically controlled knowledge needed for D.

However, neither R nor D can initiate a design process concerning ill-defined objects. This is precisely the goal of the function I, which is dedicated to the co-evolution of competencies and products.

If we accept such a viewpoint, the question arises of knowing how to organize I.

In order to answer this question they develop a model of collective action on I based on an innovative design reasoning approach. They suggest that CK is the original formalism of the design reasoning used in I.

Their research program aims at:

- defining a design reasoning based on functional logic (the concept of functional logic is presented as leading to an interpretation using the concept of a function), the expandability of the knowledge, and the expandability of the propositions;
- establishing the conditions allowing such a type of reasoning;
- defining the main operators allowing such a type of reasoning, and
- deriving more general consequences from the theory

2.2 Concepts and operators of CK theory:

The creators of the theory define design as follows [11] (p.124): "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."

Knowledge is a proposal that has a logical status for the designer or for the customer (True or False in binary logic, but the type of logic does not really matter). On the other hand, a concept is defined as a notion or proposition without any logical status: "It cannot be said from a concept whether the concept by itself is right or wrong" [3] (pp. 123-124). "Space C is the space of concepts. Concepts are undecidable propositions in K (neither true nor false in K) about some partially unknown objects x." [3].

According to the authors, design reasoning can be theorized as the co-evolution of these two spaces, C and K. What they call the "capacity of expansion" is the ability of the design process to generate innovation via reasoning which begins with a disjunction K→C, which creates a concept and ends with a conjunction C→K, which transforms a concept into knowledge.

They define the operators (C-C, C-K, K-C, C-C) which organize the co-evolution of the C and K spaces in the following manner [2]:

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". However, concepts are not alternatives but potential "seeds" for alternatives. This operator expands the space C with elements coming from K: concepts cannot be imagined without knowledge. They call this the **K-relativity** of a design process [3].

C→K: This operator searches for properties in K that could be added or subtracted to reach propositions with a logical status; it creates conjunctions which could be accepted as "finished designs" – when true. Practically, it corresponds to validation tools or methods in traditional design: consulting an expert, doing a test, an experimental plan, a prototype, and a mock-up are common examples of CK operators.

A design solution is precisely what Hatchuel and Weil call a "conjunction". They have reached a concept which is characterized by a sufficient number of propositions that can be established as true or false in K [11].

K→K: This operator allows a knowledge space to be capable of self- expansion. This operator corresponds to an expansion of the knowledge space obtained by deduction and/or experimentation. This operator is not fundamental for the design process. This operator and the following one correspond to the exploration of the design space.

C→C: Finally, the operator C→C explains the expansion of the concept space. The expansion of C (the addition of a new concept) can be performed by removing a property from a concept; it is then an inclusion. Adding a property otherwise constitutes a partition. The partition is restrictive if the property already belongs to the concept. It is expansive when a new property is added to the concept.

These mechanisms make the C space a tree structure (the partitions correspond to the creation of new "branches", expansions to their pruning). "We can only create new concepts (new sets) by adding or subtracting new properties to the initial concept." [1]

As a summary, for the creators of CK, the mechanism of expansive partition is the elementary motor of design (contrary to problem-solving approaches). The mechanism of expansive partitions therefore requires two initial conditions:

- the set to be partitioned is not completely specified. This set is expandable;
- the partition is activated using external knowledge, outside of the CK space.

The creators of CK consider that their model "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," and they justify this definition by developing an argument already developed before by Tomiyama and Yoshikawa in their General Design Theory [23]: **"**If the proposition is 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!" [11]. They claim that a false proposition in K will also result in the design being stopped.

2.3 Claims

CK appears as a very high-level theory with both fundamental mathematical roots and applicative consequences. The major claims of the creators of CK are:

1. the preservation of the consistency of definitions in K can be explained by Forcing [8], a method of Set theory developed by Paul Cohen in 1963 for the "invention" of new sets;

2. the links between design and knowledge are clarified and draw fundamental interdependences. Without concepts, no novel knowledge is possible and without prior knowledge, no concepts can emerge, otherwise how can disjunctions be made? There is no autonomous theory of knowledge;
3. CK design theory allows two extreme forms of innovation to be distinguished: conceptual innovations (great conceptual expansion without any significant expansion of knowledge) and the erroneously named applicative innovation (a great expansion of knowledge without much conceptual expansion). Hatchuel and Weil agree with the viewpoint of Kryssanov, Tamaki, and Kitamura [14], who some years earlier claimed that a "theory of creativity is a theory of transformation of the space of concepts" [21].
4. CK theory is a tool to direct and organize the innovation process [2] [4] [8]. Its creators claim that they can combine the possibility of controlling the innovation process and at the same time developing creativity by creating new islands of knowledge in the exploration phase of K.

3 A CRITICAL EXAMINATION OF THE FOUNDATIONS OF CK THEORY

This section aims at discussing the foundations of the CK theory of design. We shall consider successively the notion of concept and knowledge, the structure of the two spaces, and, finally, the operators of CK theory.

3.1 Concepts and knowledge?

The words "concepts" and "knowledge" are widely used in CK theory but also in other fields. At this point providing a greater insight into the understanding of the term "concept" is necessary. The notion of a concept is considered in two main ways in contemporary philosophical theories: as a mental representation and as an abstract object (Frege).

A concept is considered as a unit of cognitive meaning, an abstract idea, or a mental symbol, sometimes defined as "a unit of knowledge".

In modern philosophy a concept is therefore associated closely with knowledge and separating them appears artificial. From this perspective the partition between concepts and knowledge does not seem to work in modern philosophy: concepts and knowledge seem to be more dependent than they are presented as being in CK theory.

The definition that CK theory gives of "concepts" is more restrictive. This is a simple description of a set of properties a future product could have. Nevertheless, CK theory also claims that concepts are K-relative. To go further, it will be necessary to question the acceptance of the term "properties". This point is discussed later.

Analyzing knowledge requires, to start with, the questioning of the building blocks that constitute knowledge. For CK, knowledge is a proposal with a defined logical status. K is the established knowledge available to a designer (or a design team) [4]. However, in design, the literature on knowledge most commonly considers knowledge as elements that an agent (whether individual or collective, human or artificial) considers true, and this element gives him a capacity for action. It may be useful to draw distinctions between data, information, knowledge, and competence [22]. Data are elements that can be put onto a physical or virtual support (paper, mass storage data device…). They can be duplicated and shared. Data become information when the context is explicit and information becomes knowledge when the agent knows how to interpret it. Knowledge contributes to a competence when it is used for an action. All these processes (making the context explicit, interpret, use) vary from one individual to another and depend on the situation (situated action). They can also lead to cognitive shifts in distributed cognition, but distributed cognition is not considered in CK theory. As for the term "concept", CK theory gives a restrictive definition of the notion of knowledge. Fundamentally, we do not know where the knowledge that makes up the K space come from, and there is no discussion focusing on the possible contributions of the participants in the design process from their own knowledge, nor of the conditions for the mobilization of this knowledge. The creators of CK theory simply indicate that "when knowledge is lacking, the logic of the design space can create it in a controlled manner" [2] (p. 293)… but how is this done, and by whom?

This is an aspect which, like many others, remains unclarified and fuzzy in the theory.

3.2 Structures of the two spaces.

The hypothesis concerning the structure of the two spaces, C and K, must be discussed. Little has been said about a possible taxonomy of knowledge or concepts. However, these discussions are very much present in design, where classifications organized in different dimensions exist, such as product/process, or declarative/procedural. Moreover, setting taxonomies goes hand in hand with questioning the links between the different elements considered, and can be highly productive. This is an aspect not considered by CK theory.

Structure of K

The authors of this article are struck by the (lack of) structure of the K space. Propositions in the knowledge space are assumed to be relatively independent. The K space seems to have no specific structure, or, if a structure exists, it has no direct influence on the design process itself. However, this assumption for the K space does not preserve and process connections between K. The theory presents one type of connections between elements of K via the operator K→K. If the design thinking involves deductive reasoning at one time or another, then the knowledge is not independent and the organization of knowledge in the form of a father-child structure is needed in order to represent the design thinking.

The construction of concepts is made by the agglomeration of knowledge, and results (when successful) in new knowledge which is an agglomeration of existing knowledge. The path selected might be important and requires a real structure to be provided for C and K.

Nevertheless, we did not find any references to a taxonomy of knowledge in CK. There is a reference about Forcing [8], a technique of set theory that is supposed to justify the amazing capability of CK to control innovation and, at the same time, to boost creativity. Forcing is presented by the creators of CK as a justification of the structure of K. They do not refer to the term "taxonomy" but present their structure as a kind of "growing archipelago by the adjunction of new objects or by new properties linking these objects" [4]. This structure shares some properties with the definition of ontology in information science. Indeed, in computer science and information science, an ontology is a formal representation of a set of fundamental concepts within a domain and the relationships between those concepts. It is used to reason about the properties of that domain, and may be used to define the domain. An ontology organizes the domain by fundamental concepts. In this respect the knowledge space in CK theory is not structured in the form of an ontology. Hatchuel and Weil present the potential analogy between the theory of forcing and CK theory as a way to preserve meaning when new objects are created during a design process. This, for them, is the theoretical proof of the possibility of preserving the consistency of definitions in K, but this is not enough to structure K.

Structure of C

The hierarchical structure of concepts is now questioned. A fundamental feature of C is that C is not multidimensional. Concepts are constructed by additions or deletions of "properties" to an existing concept, without the nature(s) of these "properties" being discussed. Nevertheless, many developments in the understanding of design activity consider the existence of characteristics coming from several areas. This is typically the case for the functions, structures, and behavior, and possibly also the need and motivation for the product. This is also the case with the now classical hierarchy of product concepts: architecture, functions, constraints, organs… A possible source of ambiguity can arise here. For instance, an example of a concept as "something having the properties (or functions) F1, F2, F3,…" is given on page 5 in [2], whereas, on page 6, a requirement list and a proposal made by a designer can both be considered as concepts: "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." Unfortunately, we commonly consider a set of functions, a requirement list, and a proposal as different objects, and these differences have been proven to be productive. They are not considered in any way by CK theory; this is one aspect that might diminish the prescriptive aspect and the real impact of CK theory in real design situations.

More structuring could be productive

The rejection of a taxonomy raises questions. It is, for instance, impossible to discuss the concepts of co-evolution or data structures. Moreover, the reasoning cannot be fully qualified. Thus, it is significant that, for example, the concept of functionality is not present elsewhere than in the introductions to the theory.

The objective of design is linking/building links between elements of different natures. Some elements are targets (the "What For"), while others are considered as answers (the "How"). The lack of classification according to a grid-type "For What/How" does not allow complete questioning about the nature of a concept. Evidently, during design, it becomes necessary to consider propositions with a non-defined logical status, but these propositions can be of different types: "What for", "How", or, more commonly, any mix between these questions. Design can start with a complete list of requirements, as well as with very little documentation; it can also begin with an objective, with a "problem" (e.g. simply the impossibility of reaching some given objectives with the answers previously envisaged), or with the feeling that "something must be done". In this respect the structure of C in CK theory does not provide an answer to the properties needed in practical design situations.

3.3 Design reasoning

We shall now focus on the different operators involved in the development of a design. Design begins with a disjunction (K→C), then involves concept developments (mainly C→C), and ends with a conjunction (C→K). These operators deal with some design reasoning.

K→C, C→C, C→K, and K→K are the four operators used in CK theory. They were described in the previous section. CK theory is, however, not the only theory that introduces such types of operators.

Two theories, inferential design theory and the inferential theory of learning, have introduced several operators related to knowledge transmutations [13] [12]. It seems that these theories describe the knowledge processing during the design process with a much higher level of accuracy. First, the organization of inferential design theory integrates several concepts present in traditional design theory. Inferential design theory considers the memory as a combination of a representation space, design goals, initial knowledge background knowledge, and new knowledge, and sees concept generation as an inference process in which these basic elements are processed via deduction, analogy, or induction. The results can be new knowledge and/or concepts. The theory also provides design knowledge transmutations which develop the initial processes of deduction, analogy, and induction. Eleven types of knowledge transmutation are developed in inferential design theory, such as replication/destruction, insertion/deletion, agglomeration/decomposition, association/disassociation, etc…

We claim that the structure of knowledge developed in CK theory does not explicitly consider several transmutations that are present in inferential design theory. These transmutations appear to be useful in real design cases, as demonstrated by the TRIZ methodology [26] using several of these transmutation processes implicitly in order to solve design issues. CK theory seems not to consider them explicitly.

Development of C

The creators of CK say that design begins by posing a problem to be solved. But they do not give any details on the design reasoning itself. In [2], they pose a concept of “keys easy to find”, but they do not explicitly describe in which manner this initial concept emerges. They basically do not consider engineering requirements and the structure and analysis resulting from this organized phase of the development process. It gives the impression that the creators of CK considered that none of the concepts and structures developed in engineering design in the past were worth integrating into their theory.

Another issue may be the order in which we take into account the properties for the development of the tree of concepts. We did not find anything allowing the definition of an order of the properties of a concept. As a consequence, the uniqueness or non-uniqueness of the tree of concepts is not discussed in the theory. Nevertheless, the following examples show that they are important.

Let us consider, for instance, a concept such as "there exists a product with properties P1, P2, P3 …" Then where should a new concept such as "There exists a product with properties P2 and P4" appear? Obviously, this is not an expansion of {P1 and P2}. It could appear in a new branch of the tree of concepts, but in this case, the property P2 should be considered in two separate branches. Another example: "a blue machine that gives you energy and makes nice music when you caress it." Is this a blue machine that gives you energy to which we add the property "make nice music", or a machine making nice music to which we add the property blue and which gives you energy. These two definitions are strictly equivalent from a logical point of view but they will find different places in a hierarchy of concepts space as defined in C.

This is a fundamental issue in the structure of CK theory.

The first example states that even if no taxonomy is to be considered, a tree structure cannot be unique. The second example is typical of a consequence that the absence of a taxonomy can lead to, as it contains structural (blue), behavioral (making a nice sound …), and functional (gives you energy) parameters, as well as naming the object (machine).

A tree of concepts cannot be represented simply when several classes of parameters are considered, and even if only one class of parameters is considered, such a concept tree cannot be unique. Possibly, if we could limit the "properties" to one single class of parameters, things could be clearer. Functional properties could be a good choice: this aspect is often treated rapidly in current design processes, even when steady methods such as functional analysis are used, and expanding the functions could help.

In fact, the tree is built <u>by</u> the operations (inclusions and partitions). It represents the history of the construction of the concepts, and not a concept space. This appears as a limitation of CK theory. For us, this is incomprehensible because multi-dimensional representations such as those used in morphological charts have proven their efficiency in searching for concepts by systematically linking different properties: these charts consider combinations.

To sum up, the limitation to only two operations does not seem sufficiently justified and appears as a restrictive condition in the theory. We think that C could be expanded by inclusions, partitions, and also combinations.

This point will have repercussions for the descriptive or prescriptive nature of CK theory.

Switching from C to K:

The operator C→K is poorly described. "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" [4] (p 9), and this operator can also lead to the end of the design process.

But even this part of the design process is not predictable and is regularly peppered with "surprises" or unexpected findings, which are all new problems and/or opportunities.

Such unexpected findings are not fully ignored in CK. "The necessity of expanding partitions in Design explains why Yoshikawa [23] finds “unexpected functions” for a “solution”" [4] (p 9). But we must highlight the fact that an unexpected discovery is not only a property the designer can choose to add to a concept, but might also be an emergent property of this concept, fundamentally linked to it (i.e. not independent). This emergence can hardly be interpreted as a contribution from the K domain. This is, for example, one of the key tenets of the system thinking approach in considering the emerging properties that might appear in a system. Moreover, its logical status is a "status under condition": it depends on the status the concept itself will or could get. On this point, links between concepts and pieces of knowledge appear to be much more intricate than the way in which CK considers them.

In the eyes of CK theory, activities such as tests, product behavior models, prototyping, and experts, up to product development appear to be too simple and controlled processes aimed at validating the creative work made during concept generation: once you have found a concept, the design process can end (if the concept becomes knowledge, and if the product can be produced without surprise and with controlled processes) or continue with new generations of concepts. In practice, for engineers and product development what is seen as the end of the design process in CK is, in fact, just the beginning of their own design process. This aspect questions the real scope of CK relative to engineering design.

4 SOME FORGOTTEN ASPECTS OF DESIGN

In this part, after having discussed the foundations of CK theory, we would like to question the shadow zones of CK theory, to underline what seem to us to be unclear and missing aspects of the theory.

4.1 <u>Expandable rationality versus bounded rationality</u>

Hatchuel and his colleagues argue that CK theory allows us to "make operational the concept of "expandable rationality" which is opposite to one of bounded rationality (...) Indeed, "the common vision of bounded rationality seems to enclose the rational reasoning in a space of constraints which delimits the rational reasoning strongly" [3]. This argument is, however, one possible misunderstanding of the concept of Simon, who does not consider knowledge, but the cognitive cost of action.

Simon's interest was in human decision-making and problem-solving processes. He observed that decisions are not made in the way standard theory suggests, that is to say to choose a solution rationally from among existing alternatives, following well-defined criteria, and applying "substantive rationality" principles.

He presented the rationality of action from the decision-making process leading to action. He therefore also rejected the idea of the omniscient decision maker *(homo œconomicus)* and promoted the concept of *bounded rationality*.

The aim of Simon's concept of bounded rationality is not to show that individuals or organizations are irrational in their assessments and decision-making processes. The concept of bounded rationality in fact underlines the cognitive constraints the designer has to cope with.

Considering the bounded rationality [17] [18] means recognizing that even if the entire set of possible actions is theoretically given, it is not given in the practical sense because of the practical limitations of our computing resources (processing) to generate all possible actions and to compare them.

Simon characterizes bounded rationality more positively and formally by the concepts of "search" and "satisficing". His main idea is based on the "heuristic search hypothesis", which stands that "problems are solved […] by searching selectively (i.e. heuristically) through a problem space (i.e. a problem representation)" [19]. The designer begins with the recognition of a need to act: create a new artifact that should satisfy a need or improve its satisfaction. The "search" for alternatives is initiated when the designer generates solutions. Lastly, a "stop rule" is required to end this costly cognitive process. "If alternatives can not be found that are satisfying, then aspiration levels will drop until an alternative is found" [20]. This last point leads Simon to conclude that "designing is satisfying if finding an acceptable solution" [19], which is more "reasonable" or satisfactory than optimal in the sense of rational choice theory.

So, the so-called opposition between expandable rationality and bounded rationality is only apparent. It seems difficult for CK theory to accept the limits of human rationality. The expansion underlined by Hatchuel and Weil must be a bounded process.

By taking into account the bounded rationality, we focus on the impossibility of an infinite expansion of the concepts (because of the inability to treat all information that arises, because of the limitations of cognitive abilities). Then, given the speed of production and codification of knowledge that characterize modern economies, today it is attention, not knowledge, which has become a scarce resource [21] (p.25). This question is not treated in CK theory.

4.2 Design is also a social process!

Extending CK theory by integrating the bounded rationality is not sufficient because, in this way, we are still centered on the design reasoning. The design reasoning masks the crucial question of the social dimension of the design process.

Indeed, if Hatchuel and Weil [2] [4] assert that design is not only a mode of reasoning, one must note that they only considered the theory from the design reasoning perspective without considering the work division aspects and the evolution of organizational principles in design.

Indeed, in CK theory, design is considered and analyzed at the designer level, and more precisely at the designer reasoning level. However, can a theory of design which presents itself as a unified design theory forget the collective dimension of design activity?

Considering the collective dimension of design raises questions about the knowledge that designers bring to the K space, the variety of their knowledge, since resource heterogeneity provides a clear potential for creativity, and the cognitive distance between the actors, which determines their ability to cooperate effectively during the design reasoning.

Moreover, we need a theory of design which goes far beyond the design reasoning and takes into account the cultural and historical dimensions too. This is due to the fact that cultural and historical dimensions have a strong influence on the possibility of design expansion. For example, Simonton [22], considering long periods of time, showed statistical correlations between the level of creativity and the following parameters: the type of society (democratic versus autocratic), the political context (war…), or the economic one (crisis, financial disposal, number of competitors).

4.3 Design is also made of representations

In many works, design is described as an activity based on the use of product representations: drawings, diagrams, models, mockups, and numerical representations such as CAD, virtual reality representations.

The cognitive work done by designers to move from physical or numerical media to mental representations is important in design cognition.

Fundamental issues concern the way designers can express and develop their ideas through the use of representations and representation tools.

This point is certainly not critical, since many other design models, and nearly all the engineering models of designing, never consider representations and their linkage with reasoning. Moreover, an article by Tsoukias & Kazakci considers such a linkage from the concepts of the cognitive worlds of J. Gero [25].

This article points out that the design process can progress only if we introduce a third element, which they name the external representation, to the C and K space. Tsoukias & Kazakci claim that "the external representations and their reinterpretations are the main engines through which the design process progresses".

Design representation and the designers are external entities to the object to be designed. They are situated in its environment and the environment should be represented in order to allow the acquisition of knowledge.
Moreover, the problems of cognitive costs are heightened in situations of collaborative design and/or distributed design. The cognitive synchronization of the different actors takes time and resources, and organizational aspects are fundamental.
As already presented in the previous section, the human dimension is absent from CK theory because in the theory this dimension is reduced to the reasoning aspects.

4.4 What about the falsifiability of CK?

If the previous sections point out some forgotten aspects of design, in this section we would like to consider CK theory from its epistemological foundations, that is to say its consistency, its internal logic, and its falsifiability. Before considering these questions we must underline that, if some aspects of design are omitted, this cannot be an argument for the refutation of a theory. Each theory is a model of reality based on a representation of that reality. The word theory is derived from the ancient Greek theoria, which originally meant "looking at, viewing, beholding," but in philosophy the term specifically came to refer to contemplation or speculation, often based on observation or experience, providing an ideal representation, isolated from applications.
What must be considered is its internal coherence as claimed by the following definition:
a theory is a set of propositions serving to unify logical concepts in order to explain or interpret some aspects of reality.
According to these definitions, CK can be considered as a theory, and is constructed as such by the development of its basic axioms [4]. Its components are defined, axioms are given, and there are demonstrations of theorems. The internal coherence is good, and, if we have highlighted some shadow areas, this is not sufficient to attack CK on this point.
CK appears a very inclusive and comprehensive theory. At this level of abstraction it is unusual for construction defects to appear. No logical problems seem to exist at this level, except maybe on one point. The structure of knowledge and concepts are defined through their analogy with forcing theory. We suggested that a structure of knowledge and concepts organized in the form of an ontology should avoid types of logical problems such as those described in Section 3.3 (the example of the blue machine, where the structural description of knowledge and concept can lead to three different descriptions of a single concept). In CK theory some clarifications can be provided on a few points. A definition of what is called "property", a clarification of the structure (or its absence) in the knowledge space and of the "status under conditions" should help. New links between concepts and knowledge could also be added in order to account for the unexpected discoveries that we mentioned earlier. As logical propositions in K cannot be supposed to be independent of the concept(s) that generated them, their possible transposition to other concepts is questioned.

If the internal coherence of CK theory is is given a good deal of consideration by its creators, its falsifiable character is unclear. This criterion, introduced by Karl Popper, makes a distinction between theories in general and scientific ones. If CK theory happened to be irrefutable, this could strongly limit its interest and the scope of the scientific method.
What the means developed by the creators of CK theory to test the theory are is a question which remains open.
The founders of the theory should answer such questions and clearly provide such a type of study in order to clear the persistent and documented doubts about the real applicability of the approach.

4.5 How can the design process be assisted?

The capacity to assist the designer is another unclear dimension of CK theory. According to Hatchuel and his colleagues, CK theory is able to direct and guide the design process and thus the innovation process, which does not mean that the result of the design process can be known.
However, in our study we did not find any proof about the ability of the theory to control and guide the innovation process effectively.
Examples of applications of CK theory are given by the creators of the theory, but they are very general, and usually lack a description related to the context of the study and the type of cognitive mechanisms used by the designers to ensure that an innovative result is really the result of the use of CK theory.
Yet even here, the question is that the dependencies between concepts (the tree) do indicate an effect of path dependency, as stated in Section 3.3. However, we have emphasized repeatedly the lack of criteria for deciding on the action to be taken at a given time. This was the case for deciding the order in which properties are related to an initial concept or for the way a concept must be built (from which pieces of knowledge and when?). This is also the case from a process point of view for the type of evolution one should give to the concept tree: is it preferably pertinent to make an inclusion, a restrictive partition, or an expansive partition or to attempt to force a conjunction, or, given the fact that the concept tree cannot be unique, to favor a peculiar branch, or to change its structure?
The theory does not provide any guidance for answering such types of practical design questions.
In addition, CK cannot help in guiding the choice between deriving new concepts by changing the need or requirements, changing its architecture, combining new functions, or changing a product feature. It does not state, either, if we should push the analysis in the field of knowledge (K). CK does not help us to know which new knowledge is useful for a specific development. There is no mechanism described in CK to know if one should develop further knowledge in a specific area. Without any specification of such choice criteria in the design

strategy, it might be possible to consider the claims of the creators of the theory that it guides the process as excessive.
We are clear on this point; either CK claims a simple representation of effective design processes, and, in this case, it can at best be descriptive, or it claims control of the cognitive process, which, in our opinion, is not tenable, because then there is no criterion for the choice of the construction process defined in the theory. A potential useful use of CK might be the recording of a design process. Nevertheless, its creators have not claimed this type of use for their theories. In addition, the structural limitations of the theory highlighted above make the theory difficult to use for this purpose.

4.6 Process stages

There are many works on the design process, in particular Systematic Design, developed in Germany, the USA, or Japan. Although these works are well known and quoted [15] [24] [23], the creators of CK theory quote these works but do not include the several theoretical concepts used in these approaches in their theory. These aspects were developed in Section 3.2.

As we noted at the beginning of this paper, CK is an original formalism of the design reasoning used in I (Innovation) and leads us to suppose that there is no conjunction in D (Development) and no disjunction in R (Research). In this case D is then defined as problem solving; that is to say, according to CK theory, it is an exploration process which consists of the generation of a short list of possible solutions.
CK is a theory of the function I in Research Innovation Development (RID) in the model presented by Le Masson et al. [2]. This raises the question of the real contribution of CK to design and might explain why this theory seems to ignore the engineering design work in its complexity and beauty.
CK appears to be usable very early on in the innovation process since it concerns concept generation. New concepts seem close to new products, and the examples given in CK papers are, nearly systematically, examples where new functions and/or new uses are put together in a sort of functional synthesis that sometimes leads to radical functional shifts (e.g. from the initial need to develop a new smart shopping cart, the result is either a proposition to develop new interfaces between the user and the supermarket or the redesign of a smart supermarket [10]). Distinctions between process innovations, problem solving, or product improvement (e.g. incremental or radical) do not seem to be explicitly considered in the CK framework. In addition, it seems that no internal concepts in CK theory seem to specifically consider these aspects of innovation.
After the concept generation (e.g. in the "downstream" steps of a design process), there is often a need for real technical creativity, and there is no doubt that this can also be considered as a design activity. Using the CK vocabulary, this creativity is often the condition to ensure the transition from a concept (i.e. with no evidence that this concept can become knowledge) to a definition and validation of the operating principles for a product. Further, the downstream steps such as embodiment and detailed design are also not discussed in the theory.
Moreover, the theory does not address the rules for stopping the design process, named in the previous sections as a "satisfying solution". One indicator for this claim is certainly the absence of any complete product description for the examples given: except for the nail holder, the results are often reduced to principles that are never implemented. As explained above, this is one major difference from Simon, who proposed an algorithm for stopping the design process on the basis of a level of requirements [18].
There is probably a difficulty here as a result of the definition of the "perimeter" of design. If we commonly agree that design involves creativity, we also consider that the engineering design process ends with a complete description of the product. These activities should be addressed in a design theory. The impression is that CK is reduced to the conceptual phase of the design process, but, nevertheless, innovation also takes place during the later phases of the development process.
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5. CONCLUSIONS AND DISCUSSION

This paper underlines that CK is built as a theory, and that no fundamental logical defects have been found. Critics may be opposed to the choices Hatchuel and his colleagues made. But design science is an area where theoretical models of design are rare, even (almost) absent (SLM, AD), and a new theory is to be appreciated. Moreover, CK allows design to be distinguished from analytical reasoning.
The theory offers an interesting distinction between concepts and knowledge. It is often recognized and affirmed that knowledge interacts with the design process, but there is no model that takes this interaction into account explicitly. This is the case with CK theory. In this respect too, the theory seems unique. Nevertheless, the definition of concepts and knowledge as logical propositions can be restrictive and a question exists as to their real practical applicability. Moreover, it appears that concepts and knowledge could be more intricate than what CK considers. A taxonomy could help at this level.
The operators set for the development of the concept tree also seem to be restricted compared to the knowledge transmutation operators set by inferential design theory [12] [13], a theory anterior to CK, never quoted, but to which CK bears numerous similarities. Idea generation (ideation) seems complex and diverse, but here again, a restricted theory is better than no theory at all.
The theory allows the tree of concept developments to be followed. This seems quite a practical tool to trace back and record the process of designing. But is it sufficient to control the process, and to direct it? The existence of (transmutation) operators that are not taken into account and the non-uniqueness of the tree of concepts are arguments against the control claim. And the absence of criteria for the choice of the construction process (which operator to choose and which strategy?) is a strong argument against the claim that the theory directs the

innovation process. In our opinion, the theory offers a simple (but not necessarily complete) representation of design processes and in this case, it can be at best a descriptive theory of the interaction between knowledge and the early design stage. No proof was found for verifying the ability of the theory to be prescriptive and to be able to control the innovation process.

The last point that we have highlighted in this paper is the limited scope of the theory.

CK does not try to integrate the previous research progress made in design science. Most of the fundamental concepts used, such as architecture or functions, are simply ignored. Social aspects, too, are not considered. When claiming that CK covers the whole design and innovation process, its creators clearly overestimate the real scope of their theory, which, finally, appears limited to the first ideation stages. As such, this is not a problem as far as the scope of the theory is clearly established. But this limited scope leads to questions about the real impact of the theory on engineering design.

Finally, the criticisms we make of CK theory, especially the very general level of the theory and its probably limited scope, could be seen as justifications for its rejection. But this is not our opinion. CK offers an opportunity to discuss concepts; the critics highlight specificities of the very early phases of design compared to other product development phases. In this respect its formal language can be used to better grasp the specificity of the early design processes.

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