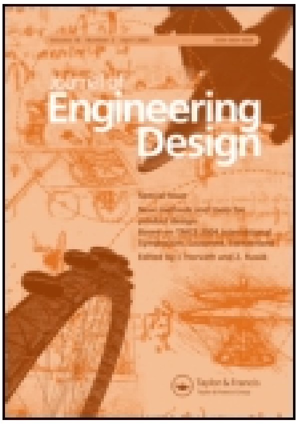

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A theoretical analysis of creativity methods in engineering design: casting and improving ASIT within C-K theory

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A theoretical analysis of creativity methods in engineering design: casting and improving ASIT within C–K theory[†]

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Approaches to supporting creativity are diverse and numerous. Making sense of these methods, including the comparative benefits of one approach over another is highly significant to both research and practice of creative design. This paper demonstrates the benefit of conducting analyses of methods with the aid of a theory. Such an approach provides a clear basis for analysing different methods that could in turn be compared with each other. This approach is demonstrated through the critical analysis of advanced systematic inventive thinking (ASIT) – a practical method – using the C–K theory, a design theory that offers a formal model of creative thinking. The analysis uncovers a paradox in ASIT operation: being creative while 'staying in the box'. While confirming that ASIT could be perceived as an implementation of some of the C–K constructs, the analysis further resolves the paradox by explaining how creative solutions could be created with ASIT. Finally, the analysis also exposes the capabilities and limitations of ASIT as well as its directions of improvement by extending ASIT operators and applying them in a linear manner.

Keywords: creativity; design theory; research methodology; TRIZ

1. Introduction

Creativity has been traditionally studied as a psychological or cognitive phenomenon that depends on individual, cultural and organisational factors (Kaufman and Sternberg 2006). Nevertheless, proposals for new methods for training and supporting creative thinking are abundant in the literature from a number of perspectives. As creativity has gained importance as an issue in the field of engineering design, it has triggered the development of its own specific creativity methods (e.g. TRIZ and advanced systematic inventive thinking (ASIT)). This move towards development of methods is an integral part of a recent formal approach to design (i.e. the C–K theory; Hatchuel and Weil 2003). Approaches in engineering such as TRIZ and ASIT are different from popular creativity methods like brainstorming, as their appropriate use requires technical background and some knowledge base of engineering domains. They also differ from standard artificial intelligence methods (and the legacy of Herbert Simon) as they are less oriented towards problem-solving and

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aim at the generation of new ideas and artefacts (Hatchuel 2001). Thus, it becomes important to understand the differences and commonalities among creativity methods in order to direct better unification and future advances, in the field of engineering design.

A recent study provided a framework for organising the space of creative conceptual design methods (Shai *et al.* 2008). The framework compares numerous diverse approaches along several dimensions and suggested ways to integrate some of them. However, the organisation and comparison were conceptual and qualitative. While the framework provides a way to organise diverse methods with a wide scope, it is insufficient to point to details of the approaches and their comparisons. In order to achieve a deeper level of analysis and propose enhancements to methods, such an analysis should rely on formal concepts and be driven as much as possible by theories. These would focus future efforts to develop methods that truly extend existing methods in different ways that would be clearly understandable to potential users.

Analysis of algorithmic methods with the aid of a theory is common in computer science where the theory of computability serves as the theoretical basis that allows comparing different exact and heuristic algorithms. In this endeavour, there is no terminological mismatch between the algorithms (methods) compared, and precise analysis allows assessing their relative merit. In addition, each such an analysis makes assumptions about the nature of problems that are addressed by the algorithms. Therefore, the analysis is contextualised in the formulation of design problems.

As shown by Shai *et al.* (2008), there is hardly common terminology or shared conceptual basis in creativity studies; therefore, our study first has to establish such common ground and then conduct a conceptual comparison. Since design problem formulations are so diverse, ‘performance’ analyses of methods is not addressed in this paper.

In our analysis, we chose to model a creativity method, ASIT (Horowitz 1999), with the help of a design theory, the C–K theory (Hatchuel and Weil 2003), that incorporates creative thinking. Both approaches, ASIT and the use of the C–K theory in practice, support creativity and have enjoyed industrial success, yet they are built on different levels of generality. The first is presented as a method with empirical validation of some of its assumptions derived from practice (Horowitz and Maimon 1997, Horowitz 1999). The latter is presented as a theory of designing that embeds creativity as an integral part, and is supported by theoretical results as well as empirical evidence of its applicability (Hatchuel and Weil 2003, 2007, 2009). The purpose of this study is to analyse ASIT – the method using the language of the C–K theory.

This study demonstrates that:

- A theory-driven comparison offers precise and detailed results on the logical and empirical assumptions of the methods that are complementary to non-theory-based comparisons that have been employed in the literature.
- ASIT is a specific, yet paradoxical creativity method, based on ‘stay in the box’ principle that seems contradictory with standard views about creativity. Modelling ASIT as a special instance of the C–K theory resolves the paradox and shows that ASIT is well adapted to a class of design situations. This enhances the theoretical status of ASIT and allows a precise formal modelling of ASIT instead of a list of broad notions, which is the common presentation of ASIT.
- Moreover, the model shows that ASIT can be improved and extended by a step-based knowledge expansion that can progressively break the ‘stay in the box principle’ and introduce degrees of ‘near of the box principle’ while keeping the validity of other ASIT principles.

These initial findings invite us to conduct additional studies to improve our understanding and classification of existing creativity methods using the modelling power of C–K as a theory of creative designing.

The remainder of this paper is organised as follows. Section 2 describes the methodology of this study. Section 3 reviews both approaches including an example of using ASIT. Section 4 presents a model of ASIT within the C–K theory that helps us to identify the 'ASIT paradox' and to discuss ASIT's strengths, limitations and possible improvements. Section 5 discusses the comparison, drawing conclusions about the relative status of ASIT and C–K and extends the analysis to creativity methods such as TRIZ (Altshuller 1984) and unified SIT (USIT) (Sickafus 1997) that are closely related to ASIT. We conclude the paper by outlining further steps into a systematic and comparative analysis of creativity methods.

2. Methodology: a theory-based analysis of creativity methods

In many situations, comparative analyses of methods are done verbally by describing what each method is doing. Most often, such description employs the idiosyncratic terminology used to describe the method. While its value is limited, this is the common way to write literature review in publications. Another form of analysis involves the use of some conceptual framework for organising some collection of methods (e.g. analysis of creativity methods; Shai *et al.* 2008). The value of such an analysis depends on the quality of the framework and the ability to represent the methods within that framework. A more time-consuming analysis takes a collection of tools with or without some organising framework, and uses them to solve benchmark problems (e.g. the use of high-level system design tools; Bahill *et al.* 1998). The experience and results of such solutions are used to compare the methods. The value of such an analysis depends on the choice of the benchmark problems and the ability to generalise from such problems, which are often simple, to real complex problems. These three analyses methods allow us to appreciate to varying degrees, *what* is the difference between different methods and *what* is the difference between the results they produce. However, they provide little support to understand *why* different methods produce different results.

In an attempt to uncover a deeper understanding of methods, some studies have concentrated on performing only pairwise comparisons of methods. The idea is that through such concentration, the analysis could really touch upon the differences and uncover them. In the special context of engineering design, pairwise comparisons of creativity or design methods have been done before. The studies included a comparison of TRIZ (or TIPS) and Pahl and Beitz's design method (Malmqvist *et al.* 1996) and a comparison of TRIZ and USIT (Nakagawa 2005). When the methods differ significantly in scope, the problem of different terminologies arises and the analysis becomes qualitative.

The nature of the comparison depends on the goals of the study. A goal to integrate methods into a single process could lead to a loose qualitative comparison (Shirwaiker and Okudan 2008). A goal to understand the differences between the methods could lead to match important concepts such as 'conflict' (Kim and Cochran 2000). An interesting part of the latter study is that it shows the lack of agreements among researchers of the same method (i.e. TRIZ) with respect to its capabilities (i.e. addressing functional coupling exemplified by the example of faucet design; Kim and Cochran 2000). Such disagreement that is not resolved points to the limitation of qualitative or textual comparison between methods.

A popular comparison is between axiomatic design (Suh 1990) and TRIZ. The interesting aspect of this comparison is that axiomatic design is described concisely into axioms that could be compared with other approaches (Yang and Zhang 2000). More generally, comparisons that are more precise could follow if directed by a theory. The concepts of the theory could be used to explain the scope of the method and point clearly to differences and overlaps. The theory could provide the explanatory power that would help uncover the reasons *why* different methods perform differently and why proposed changes could improve a method. The value of the analysis is based on the use of the theory as a precise conceptual framework with clearly articulated concepts; the value also depends on the credibility of the theory.

This leads to the fourth type of analysis: comparing methods by analysing each with a theory, thus exposing in detail the reasons for its performance. If this analysis is repeated for different methods, the insight regarding their relative performance also becomes available. To initiate such a comparison, this paper starts by conducting a theory-driven analysis of a single creativity method. The goals of the study are to derive value for better understanding the method's performance including potential and limitations and through this example demonstrate the value of theory-driven analysis. We selected to analyse ASIT – a creativity method that enjoys practical success and that was partially validated in laboratory experiments. Nevertheless, the source of power of ASIT is theoretically unclear, and moreover, part of its basis seems paradoxical as discussed later. ASIT is a simplification of TRIZ yet simpler to learn and understand, which makes its analysis easier to comprehend by unfamiliar readers.

The selection of the theory is rather simple as there is only one candidate theory that both offers a formal modelling and embeds creativity as an integral part of design, namely the C–K theory. Due to its formal structure, the C–K theory offers a variety of testable propositions. A complete and systematic empirical validation of the C–K theory is an ongoing project. In addition, since its initial presentation, the C–K theory has been used to explain different design phenomena and guide creative design processes (Hatchuel *et al.* 2004, Dym *et al.* 2005, Elmquist and Segrestin 2007, Elmquist and Le Masson 2009, Elmquist and Segrestin 2009, Hatchuel and Weil 2009, Gillier *et al.* 2010, Gobbo Jr. and Olsson 2010).

The analysis that follows reveals the relations between ASIT and C–K, explains the sources of power and limitations of ASIT and hints at a potential enhancement to ASIT. In a subsequent paper, we analysed the method of infused design (Shai and Reich 2004a, 2004b) with the C–K theory (Shai *et al.* 2009). We leave as future work the framing of other creativity methods within the C–K theory so that we can ultimately compare all these methods within a single theoretical framework. The analysis also reveals the need to conduct a detailed study on measuring creative processes. While measures for creative products have been proposed with limited agreement among researchers, measures for creative processes have been lacking primarily due to the lack of a theoretical foundation for describing creative processes. With the C–K theory, such measures could be proposed and studied. A preliminary analysis on creativity measures is given in this paper, but an in-depth treatment is left for a future study.

3. Review of the ASIT and C–K theory

This section reviews the basic concepts of the C–K theory and ASIT. Further details appear in the aforementioned references.

3.1. *ASIT: the paradox of engineering creativity under the CWC*

ASIT is a method for supporting the generation of creative ideas. The ideas that ASIT fosters need to be elaborated further into solutions proposals whose implementation has to be validated. ASIT does not promise to find a solution, just to bridge some of the gap between complex problems and their solutions. This seems to be a property of most, if not all, creativity-enhancing methods (Shai *et al.* 2008). ASIT evolved as a response to the perceived complexity of TRIZ. It was evolved and partly tested in laboratory and industrial settings to support its principles. As such, it could be perceived as a validated method.

ASIT is based on one *condition*, one *principle* and five *operators* (or tools). They are quite simple to understand and could be taught in few hours, yet they raise important issues.

- The major condition of ASIT seems in contradiction with the standard view of creativity: instead of the common ‘out of the box’ principles, it insists on ‘the closed world condition’ (CWC).[1] It states that the objects that exist in the system at the time of the problem are those that would be used to address it. This means that once a problem is defined, the objects that should be used to solve it are known! Such a condition seems paradoxical because how can we reasonably solve a problem by only considering parts that participate in the problem. How is it possible to be creative or generate something new by staying inside the (system or world) box? The answer to this might come from a careful theoretical analysis as we show later.
- The ‘achieving qualitative change principle’ (QCP) directs to look for solutions in which the influence of the main problem factor is eliminated or even reversed. This principle can be seen as a development of the contradiction elimination in TRIZ.
- Once the CWC is used to specify the problem world, considering only those elements that compose the problem and its nearest environment, ASIT provides five operators that detail specific hints that could subsequently lead to a solution. The five operators are:

    (1) *Unification* solves a problem by assigning a new use to an existing component.
    (2) *Multiplication* solves a problem by introducing a slightly modified copy of an existing object into the current system.
    (3) *Division* solves a problem by dividing an object and reorganising it parts.
    (4) *Breaking Symmetry* solves a problem by changing a symmetrical situation into an asymmetrical one.
    (5) *Object Removal* solves a problem by removing an object from the system.

Some of the authors are teaching ASIT to high school and university students and seeing its use in subsequent exercises as well as design projects. Students are capable of using ASIT to generate solutions after several hours of teaching (e.g. Kolberg *et al.* 2007). These capabilities have also been shown in laboratory tests when the method was developed.

ASIT example: Consider the use of the unification tool to solve a classic TRIZ case study. The case deals with an experiment for checking whether a material is resistant to acidic environments. Samples of metal cube materials are placed in different environments with different pressures and temperatures inside a closed metal container. After the test, the samples are inspected to detect any erosion. Samples are taken out of the vessel; they are examined to test how the acid affected them. The problem is that the vessel itself is damaged by the acid.

The solution of this problem using the unification tool is given in Table 1. While this tool seems to solve the problem, the other four tools could be used as well to provide other hints.

Clearly, ASIT tools and principles allow the systematic generation of a surprising idea while only using objects of the system. Yet, once we attempt to implement the solution, we could face complications that are outside the scope of the original problem definition.

For example, the impact of acid on material highly depends on the surface finish of the material. A drilled hole could hardly be finished as a flat surface that could be polished and rough surfaces are much more susceptible to corrosion than polished surfaces. A better solution would be to machine a pocket in the sample.

In addition, a polished surface would be free of residual stresses, while the hole or even pocket surface would have residual stresses that are likely to undergo stress-induced corrosion. This effect would be present more in materials that are difficult to machine such as titanium alloys. Consequently, the solution must at least include heat treatment following machining.

In summary, to be a complete solution, the idea derived from ASIT needs to be elaborated much further. Through this elaboration, new objects or new object’s properties might become important, requiring a modification of the initial problem definition. Thus ASIT presents a paradoxical form of creative reasoning: in order to find surprising ideas it insists on systematic ‘in the box’ explorations of the system. Yet, the further elaboration of these ideas might need an ‘out of the box’ strategy.

Table 1. The acid test problem solved with ASIT's unification tool. The last two columns are discussed later in the paper.

Tool template	Example	Explanation	C–K	Step in Figure 4
1 Define the problem world (following the CWC)			K	1
Make a list of problem objects	ACID, CONTAINER	The objects involved in generating the undesired effect. This explains why the SAMPLES are not listed here – they do not harm anything and are not being damaged	K	2
Make a list of environment objects	SAMPLES, AIR		K	
2 Prepare for unification			K	
Define the undesired effect (the problem definition)	The ACID attacks the CONTAINER	A short and factual description of the problem. It usually takes the form of stating what damage object X inflicts on object Y. Please note how simple and non-creative this definition is. ASIT prevents the problem-solver from trying to be too smart at the wrong stage in the problem-solving process	K	2
Derive the wanted action that eliminates the undesired effect (using the problem solution template of the particular tool)	Prevent the ACID from attacking the CONTAINER	Usually derived from the undesired effect by adding the words 'to prevent . . .from. . . '.	C	3
Select an object to perform the wanted action (referred to as a focal object)	SAMPLES	Select one object at a time until arriving at the solution	K → C	4
3 Apply unification			C → C	5
Imagine the selected object performing the wanted action. Note that this and other objects could be modified		Here we simply have to imagine the SAMPLES preventing the ACID from attacking the CONTAINER. (Each of these three objects can also be modified to help prevent this.)		
4 Define your core idea in one sentence	The SAMPLES will contain the ACID, thus preventing its contact with the CONTAINER		C → C	6, 7
5 Elaborate the idea in 3–5 sentences	Drill a pocket in the samples and pour the ACID into the pocket. The ACID will not contact the CONTAINER. The SAMPLES need to be large enough so that the ACID will not leak out	Sometimes this elaboration is clearly realisable and sometimes it needs to be validated through experiments or even careful design, implementation and test	C → C, C → K (if clearly true in K)	7, 8
(Repeat steps 2–5 until you arrive at a satisfactory idea)				

Source. Adapted from Horowitz (2001).

Is ASIT a consistent method? To model ASIT assumptions and clarify them, we will use the language and results of the C–K theory.

3.2. *C–K theory: a model for creative design*

In the field of design theory, C–K theory has been introduced by Hatchuel and Weil (2003) and has been receiving growing interest in the literature. Its implementation as a method has been used in different industrial settings. A recent publication offers an overview of the main discussions and applications of C–K theory (Hatchuel and Weil 2009). One of the central properties of C–K theory is its proposition to model creative thinking and innovation as a constitutive part of the design process. Moreover, the propositions of C–K theory are built at a highly abstract level which requires second order logic and its consistency is warranted by basic results from modern Set theory (Hatchuel and Weil 2003, 2009). Thus, C–K theory may be seen as a general and formalised model of creative thinking that can be used to analyse the specific assumptions of creativity for engineering (Hatchuel *et al.* 2008).

3.2.1. *Elements of the C–K theory: C-space, K-space and C–K operators*

(a) The C–K theory makes use of two spaces: (1) K – the knowledge space – is a space of propositions that have a logical status for a designer; and (2) C – the concepts space – is a space containing concepts which are propositions, or groups of propositions that have no logical status in K. This means that when a concept is formulated it is impossible to prove that it is a proposition of K. Design is defined as the process by which a concept generates other concepts or is transformed into knowledge, i.e. propositions in K.
(b) Concepts can only be partitioned or included, not searched or explored. If we add new properties (K → C), we partition the set into subsets; if we subtract properties we include the set in a set that contains it. Nothing else can be done. After partitioning or inclusion, concepts may still remain concepts (C → C), or move to propositions of K (C → K). The two spaces and four operators (including the K → K) are shown in Figure 1.
(c) A space of concepts is necessarily tree-structured as the only operations allowed are partitions and inclusions and it has initial disjunctions. Yet, we need to distinguish between two types of partitions: restrictive and expansive partitions.

- If the property we add to a concept is already known in K as a property of one of the entities concerned, we have a *restricting partition*; for example, if we are designing a 'smart house', and if we partition it with standard house elements in K (e.g. walls, roofs, etc.), we form a restricting

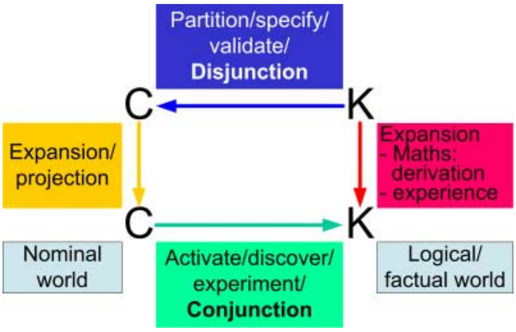

Figure 1. The design square modelled by the C–K theory (Hatchuel *et al.* 2004).

partition. If the property we add is not known in K as a property of one of the entities involved in the concept definition, we have an *expansive partition*. In the 'smart house' example, if we choose to partition by 'new types of energy saving strategies', and if some of these strategies are not known for all houses in K we have an expansive partition.

- This distinction leads to important theorems that can be proved in the theory (Hatchuel and Weil 2009):
  - C0, the departure concept is necessarily an expansive partition.
  - If the partition of C0 uses only restricting partitions, there is no design solutions, thus any design solution needs at least one expansive partition different from C0.
  - Expansive partitions can lead to design solutions only if there are K-expansions that validate them or generate new expansive partitions.

These results offer a general model of creative design and its main properties are reviewed later in Section 3.2.2.

(d) Another view of the C–K dynamics is given in Figure 2. We recognise the necessary tree structure in C, while the structure in K could be completely different. We also see in this picture that any expansion in C is dependant of K and the reverse is true. Any choice to expand or not in C is K-dependant. Conversely, any creation in K requires traversing some path in C. Design begins with a disjunction and will end only if some conjunction exists that is judged as an acceptable solution.

3.2.2. *C–K theory as a model of creative design and thinking: main properties*

Classically, creative thinking has been related to broad notions like 'divergent' forms of thinking and to the capacity to think 'out of the box' and generate novel ideas which strongly differ from accepted solutions or dominant designs. Metaphors, analogies, surprising associations as well as serendipity have been recognised as direct means of creative thinking. Can the C–K theory model all aspects of creative thinking? This would require an elaborate answer and will not be addressed in this paper as its focus is not the C–K theory per se. In this article, we only focus on the C–K theory as a modelling tool for engineering creativity that generally use standard forms of Knowledge (technical, social, economic, etc.) and describe the reasoning steps.

In the engineering creativity context, the C–K theory offers clear definitions of common notions used in creativity methods and it establishes necessary conditions to design (or create) objects that were unknown at the beginning of the process.

(P1) *Concept definition*: what is usually called 'an idea', or a 'brief' or even 'a concept' in the literature of creativity has some pragmatic and experiential meaning but no scientific definition. The C–K theory establishes that:

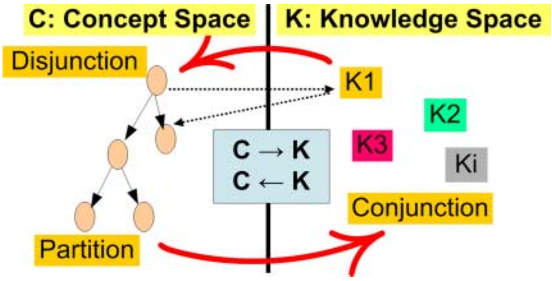

Figure 2. The C–K dynamics (Hatchuel *et al.* 2004).

(i) *all these notions designate one same class of propositions of the form* C-*type*: ‘there exists some partially unknown X which possesses some properties $P_1, P_2, \dots, P_k$’.
(ii) *Necessarily,* C-*type propositions are undecidable in* K; otherwise, they would belong to K and design would stop.

(P2) *Concepts are a necessary condition of creativity,* but not a sufficient one. The creative design process needs the transformation of undecidable propositions into decidable ones (i.e. knowledge). In other words, ‘new ideas’ are only one ingredient of creative design.

(P3) *Concepts are necessarily formed by expansive partitions*: Undecidability can only be obtained by partitions that are not already known in space K.

(P4) *The creative design process requires necessarily both* C-*expansions and* K-*expansions*: To transform an undecidable proposition in C into a decidable one in K, new knowledge is required to generate new expansive partitions (K → C) or to validate them in K (C → K). In return, new knowledge is triggered by concepts (C → K). Hence, the four C–K operators are all necessary to generate new objects (new designs) in K.

Hatchuel and Weil (2009) illustrate these propositions using the case of designing a new type of engine for Mars explorations. They show how the initial concept ‘an Mg–CO_2 engine for mars exploration’ is transformed into a new concept of vehicle for a new type of missions on mars. During the process, both new concepts and new knowledge were generated. To summarise, the C–K theory provides: (i) a set of notions and propositions that avoids the broadness and equivocality of usual creativity language; (ii) it establishes necessary conditions that should be verified by any creativity method and (iii) it can model the consequences of neglecting one of these conditions.

For all these reasons, the C–K theory appears to be a good analytical framework to analyse the ASIT assumptions and to characterise its creative logic or its limitations. This will be illustrated in the next sections where we discuss the creative power of ASIT and then propose a model of ASIT in C–K constructs.

3.2.3. *C–K theory and the metrics of creative design: first evaluation of the creative power of ASIT*

The formal structure and explanatory power of the C–K theory have implications on the metrics of creativity in design. It is well known that creative design could be evaluated through its process or through its outcomes. But the literature has been largely focused on the latter type of evaluations due to a lack of consistent design process theory and on the observation that ‘to date we do not have any comprehensive models of design creativity developed on scientific foundations’ (Shah *et al.* 2003, p. 133). The C–K theory challenges such views of the ‘state of the art’ in design and presents a process with foundations in modern Set theory (Hatchuel and Weil 2007, Kazakçi and Hatchuel 2009 that has not been reached by other design theories (e.g. general design theory (Tomiyama and Yoshikawa 1987) or its topological generalisation (Braha and Reich 2003)). Consequently, it becomes possible to study the meaning and validity of metrics for creative design from a theoretical point of view that is complementary to methods based on outcome judgements. This issue is beyond the scope of this paper and will be addressed in future works. However, some straightforward propositions can be derived from our brief presentation of the C–K that will be of direct help, in this paper, for the study of ASIT.

(a) *Multidimensionality and K-contingency of evaluations*: Creativity in design can be explained as the result of the interaction of four distinct C–K operators. The multidimensionality of the C–K operators explains the theoretical and practical difficulties in explaining creativity, well acknowledged in the literature.

Establishing one unique metric of this process: Any metric will be conventionally linked to the evaluation criteria and weight that is associated to each of the C–K operators in the final formation of the creative design. If validation operators (C → K) (for example, some judgement on the feasibility or economic value of the ideas) are seen as an essential aspect of creative design, the only solutions that will be viewed as creative will be those designs that have proven their technical and/or market success. As pointed by Shah *et al.* (2003), this type of evaluation contrasts with the traditional perspective of creativity studies where creative ideas are evaluated regardless of the ability to realise and to use the design. Moreover, each C–K operator could be evaluated and associated to some metric. And the C–K theory draws our attention to aspects of creative design that are insufficiently discussed in the literature. For example, one could judge a creative design process through the creativity of its prototyping strategy (a combination of C → C operators and C → K operators) – an issue that is crucial in real engineering design situations where the speed with which ideas are redesigned and their novelty maintained is of paramount value.[2]

Yet, each metric of creative design will be contingent on some specific purpose and on the assumptions about the state of knowledge. The design process is relative to a common knowledge K0 that should be shared by the designer and any judge that evaluates the proposed design solutions. If there is no common state of knowledge between two design evaluators, their evaluation will be different. In practice, this means that any judgment about *novelty and usefulness,* the standard criteria in the literature, is contingent on a specific state of knowledge that should be specified in as much detail as possible.[3]

(b) *The limitations of 'black box' expert judgements on design outcomes*: The prevalent tradition in the literature about creativity is to evaluate creative ideas, and not validated designs through expert judgements (Horn and Salvendy 2006). This is based on a kind of 'black box' assumption that 'people can identify a creative idea when they see one, but are unable to supply an a priori list of properties which constitute a creative idea' (Horowitz and Maimon 1997). However, this assumption could lead to the risk of circularity. If we do not know how and why people judge that an idea is more or less creative and if we validate a creativity method only through expert evaluation, we may simply *select the methods that best correspond to the implicit views of creativity among the evaluators*. Let us use an analogy and assume that we want to evaluate 'uncertainty'. If we use only expert judgements, we will only access the perceptions about uncertainty. Now, it is obvious that the development of the probability theory has changed our understanding and control of uncertainty. At least, it helped to see differences between the common perception of risk and the models of risk suggested by the theory. Similarly, the C–K theory offers a controllable[4] model on the evaluation of creative design. It will allow us to explain expert judgements through preconceptions and biases about creative design as in the case of ASIT, which is discussed in the next sections of this paper.

(c) *A dual framework for the evaluation of creative engineering design*: As we said before, according to the C–K theory, a creative design can be obtained through four types of operators. Thus, the evaluation of any design should study the contribution of a designer in these four types of activities. In classic creativity tasks, some of these operators do not appear. Yet, in the field of engineering, all operators may play an important role in the formation of a creative design. For example, the introduction of a new mathematical simulation model can provide insights into new interesting concepts. In this case, design creativity benefits from a K → K operation, which is an operation of *knowledge transformation and reordering*. This type of approach is not always seen as 'creative' but merely as an 'analytic' or 'scientific' way to generate ideas. Shah *et al.* (2003) have already remarked that creative design differs from standard creativity tasks because relevance and quality are needed to evaluate designs. But the C–K theory allows us to extend these differences to the creative process itself. The process of creative engineering design needs more than creative ideas; it needs a knowledge-creating process that supports the validation of these ideas but also helps to expand the creative ideas beyond the domain of existing possibilities, which is the core logic of innovation in engineering. In C–K terms, we can say that classic creativity tends to call for an evaluation in the C-space, while engineering design will be built on creativity within both C and K space and their interactions. This leads at least to a dual logic of evaluation: one in the space C and one in the K space.

(c1) *Creativity in space C: evaluating C-expansions.* The dynamics of space C is characterised by *expansive partitions*, i.e. attributes that are tentatively assigned to some objects in a way that does not exist in K. In the acid test example, the idea of making a hole in the sample is not an expansive partition, while putting the acid in that hole is an expansive partition if and only if there is no known case in K of a test that uses such types of samples, accessible to the designer. Thus, one type of evaluation of a creative design should be built *on the nature and distribution of expansive partitions that participated in the design solution*. One creative design may result from several expansive partitions. However, some of them may be invisible or absent in the final design but may have been crucial in the generation of new knowledge that finally helped to form another expansive partition that led to the final design (Hatchuel and Weil 2009). Unfortunately, most studies evaluate a new design idea and not the set of expansive partitions that led to it. This is similar to judging the creativity of a mathematical finding without knowing all the sequences of the derivation. With such limited information, we can predict that the evaluation of the creative design will be linked to *its most visible and surprising expansive partitions*: those that impact objects that are well known to the evaluator (i.e. large set of properties in K) and use partitioning attributes coming from seemingly independent subparts of K0. For example, in the case of the acid test, the surprise comes from the use of the sample as a protection system for its environment, which is not the case in any of the tests known to the designer or to any judge of the solution. Thus, any rigorous evaluation of creativity in space C needs to capture the *complex pattern* of expansive partitions during the design process and not only those that are visible through the final design.

(c2) *Creativity in space K: evaluating K-expansions*. This second dimension is usually absent from classic creativity evaluations which seek to evaluate the pure creative capacity of a person independently of its expertise or its knowledge generation capabilities. But missing such dynamics is not appropriate for the evaluation of creative design where creativity may be obtained through a process of knowledge expansion (acquisition or production). For example, let us compare two designers, 1 and 2, that have to design watches that are thinner and lighter than existing ones and let us assume that their knowledge are similar at the beginning of the process and are only based on mechanics. Designer 1 redesigns carefully all arrangements and organs and reaches outstanding performances but stays in the domain of mechanical watches. Designer 2 explores many recent findings on quartz properties and designs the first quartz-based watch with the same performances. Who should be considered more creative?[5] Actually, one can consider that these designers use two different classes of operators of creative design that should not be compared. The C–K theory includes both logics in the same model. The discovery and utilisation of new knowledge (i.e. that was not part of K0 at the beginning of the process) is a major dimension of creative engineering design. It corresponds to a class of engineering design processes where the technological solution that is finally used was not known to the designer at the beginning of the process. The evaluation of such K-expansion during the process requires a different set of criteria than evaluating C-expansions. Not all K-expansions are interesting or necessary and what counts is how this new knowledge helps to open a variety of ideas or solutions that would not exist without it. Moreover, the knowledge discovered during the process may be much more important than the initial design challenge. In such a case, the design project becomes a template for the development of a completely new domain. This type of design dynamics is typical of major breakthroughs in engineering, for example, the design of transistors, of ductile tungsten ductile or of silicium-based electronic circuits are well-documented examples of such innovative engineering designs where the production of new knowledge was a vital part of the design process.

3.2.4. *Evaluating the creative power of ASIT in C and K: first discussion about the CWC*

In one of the most detailed evaluation of ASIT, Horowitz and Maimon (1997) presented a quantitative survey based on expert judgements on the compared creativity of several solutions to a list of design problems. In addition, they classify these solutions into two groups: (1) the group of solutions that respect two main ASIT principles: the CWC and the QCP; and (2) the group of solutions that do not seem to fulfil those conditions. The collected data support statistically the idea that experts tend to judge as more creative the solutions that respect the two ASIT conditions. Consequently, Horowitz and Maimon concluded that such data establish the creative power of ASIT. From the point of view of C–K theory, there are solid reasons to interpret these observations in a reverse way. We have seen before that when experts have to judge the creative degree of design solutions they will tend to recognise creativity only through visible C-expansions that act on known and perceived objects of the system. In the next section, we will establish with more detail that the CWC mechanically guides the design process towards such a type of C-expansions. Thus, evaluating ASIT through expert judgements runs the risk to create a circular validation process. ASIT could appear as a more creative methodology not because it really favours all the operators of creative design (at least those that have been identified by C–K theory) but only because it only uses those operators that are more perceived as creative by external experts that may have limited knowledge and experience with the problem.

A second critical aspect of these expert evaluations stands in the ambiguities of the CWC that could lead to neglect K-expansions even if they play a crucial role in the determination of a design solution. This can be illustrated using an example that is presented by Horowitz and Maimon (1997).

Solid fuel Rocket engine designers have to maintain a constant thrust from the engines (see Figure 3(a)). Among the solutions to this problem, the one that is considered as the most creative uses a special form of solid fuel which keeps a constant burning surface during the combustion (Figure 3(b)). Now can we consider that this solution fulfils ASIT's CWC? The solid fuel is an object of the system that is maintained in the new design. But the new shape is a new object that has been introduced in the system and can only appear after a process of knowledge acquisition and production. If one considers the knowledge that is needed to reach this solution, it is clear that the identification of a shape that burns with a constant surface needs a specific mathematical ability and a capacity of combustion modelling that is not a standard background of all engineering experts. Thus, following the closed world principle could prevent such a solution by inhibiting the exploration of different sources of knowledge than those which seem direcly linked to the object of the systems. It clearly means that K-expansions are not considered as a dimension of creativity in ASIT.

Thus, the C–K theory introduces new perspectives for the evaluation of creative design. It invites to build criteria that can be clearly linked to all operators that contribute to the creative design process both in C space and K space. It allows us to discuss what can be learned from

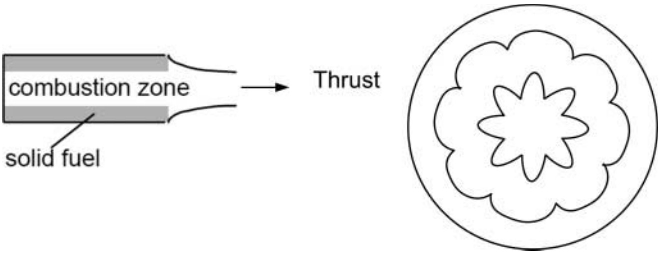

Figure 3. Solid fuel rocket engine problem (after Horowitz and Maimon 1997): (a) side view; (b) the new inner envelope as combustion progresses.

expert judgements and opens the possibility to reach evaluations that are based on solid theoretical grounds. This has already helped us in an initial evaluation of ASIT, that will now be deepened by a more thorough modelling of ASIT's operators with C–K constructs.

4. Modelling ASIT with the C–K theory: the paradox of 'in the box' creativity

4.1. *ASIT activities and C–K constructs: a straightforward correspondence*

ASIT has no explicit C or K constructs in its description; there is no distinction between the two. Once cast in C–K constructs, its operation could be explained as transformations between C–K spaces. The one before last column in Table 1 specifies the type of space and operator in the C–K theory for each ASIT activity. For example, defining the objects in the problem world involves use of K constructs, as they are existing objects with observed or examined properties and behaviours. In contrast, the desired outcome, 'Prevent the ACID from attacking the CONTAINER', is a C construct, as the status of this statement does not have truth value. It certainly does not refer to an existing object but to a property of an object awaiting discovery. Selecting an object from the problem world as a potential solution for this prevention, e.g. 'SAMPLES', is a transformation of this K construct into the C construct 'the SAMPLES will prevent the ACID from attacking the CONTAINER'. Again, this statement has no truth value until the exact details of this prevention are described and verified to work in reality.

Figure 4 illustrates this graphically by showing how the different ASIT steps that use the condition, principle and the unification tool map to C–K spaces and operators. These steps appear also in Table 1. (1) The CWC helps in identifying the boundary of knowledge in K that is going to be considered for obtaining a creative solution. (2) The problem definition includes the objects in the closed world, the relations between them and the problem requiring solution. (3) The problem solution template in each of the tools moves the problem statement into a potential solution in C. (4) The addition of a focal object, the one selected among the problem definition to address the problem completes the solution statement in C. (5) The five tools offer templates that refine concepts in the C space. (6) The templates are simple elaborations that bring additional objects from the problem definition (K) into C to form new concepts. The mental elaboration that each tool demands and the write-up that follows are supposed to provide additional details that maintain the idea in the C space. (7) The QCP guides the refinement process in the C space followed by checks at the K space. (8) Any implementation moves the concept into the K space. An attempt to implement might fail, thus retaining the idea in the C space. (9) An implemented idea in K is

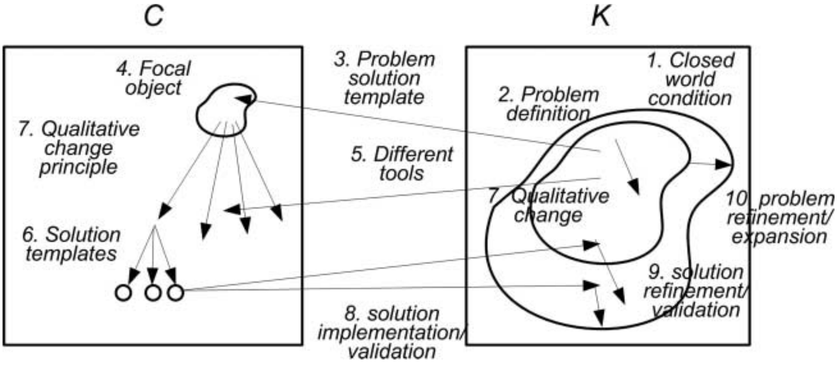

Figure 4. ASIT in C–K spaces.

not necessarily a good solution if it turns out that the original problem definition missed critical items. (10) This would require expanding the boundaries of K and including additional problem or environment objects into the problem definition.

This first correspondence illustrates how the highly general language of the C–K theory (i.e. 'expanding partitions' (K → C), C-expansions, K-expansions) captures clearly the activities of a creativity method. Yet, the C–K says nothing about 'how' expansive partitions should be generated from K. Although ASIT and other creativity methods adopt a heuristic approach to this 'how' issue, they do not theorise the whole design logic but offer special techniques to guide and systematise the generation of expansive partitions, *taking into account some feasibility and workability issues* such as staying in the system, acting on one part at a time, or using only existing objects.

4.2. *Solving the ASIT paradox and improving strategies of the method*

What is the specific logic of ASIT? ASIT is formulated in traditional engineering language: system, objects, use, parts, etc. ASIT's operators are presented with interesting and evocative expressions that requires background to interpret (e.g. 'unification' or 'multiplication'). To clarify the comparison with the C–K, we need to capture ASIT in a more formal language without losing its value.

4.2.1. *Capturing ASIT logic in C–K constructs*

The structure of space K. ASIT assumes a specific K space containing two parts:

(1) Ks: existing knowledge about some system S.
(2) Ke: existing knowledge about all known objects that are not in S. Ke describes some standard knowledge that is easily activated and can be used in addition to Ks: like 'drilling a hole' in the sample is common knowledge. Outside Ke and Ks, ASIT models no knowledge that could be discovered during the creative process.
(3) ASIT defines Ks as a system consisting of:
    - A finite set of objects: O_i, $i = 1, \ldots, I$
    - A finite set of relations between these objects: OR_{ij}; $i, j = 1, \ldots, I$
    - A finite set of performances (or functional requirements): FR_k, $k = 1, \ldots, K$
    - A current working system: the system where $(\mathrm{O}_i, \mathrm{OR}_{ij}) \to \mathrm{FR}_k$
    - Any O_i is decomposable into parts ($\mathrm{PO}_{i,l}$; $l = 1, \ldots, L$) and relations between these parts $\mathrm{POR}_{i,lm}$; $l, m = 1, \ldots, L$[6] (*Parts are known in* Ks)
(4) With the preceding notations, we can capture the specific content of the CWC in ASIT:
    - Design will only use: Ks, Ke, O_i, OR_{ij}, $\mathrm{PO}_{i,l}$, $\mathrm{POR}_{i,lm}$, and FR_k
    - No entirely new object or part of an object is discovered during the process. No K-expansion is allowed.

The structure of space C and the first C0. ASIT's creative design logic can now be clarified.

(1) *The QCP* means a design process guided by a specific concept C0: 'a system S' which is the closest possible to S, easily workable, respecting CWC, and so that some new FR* (or a group of new FR*s) which is not a property of S can be warranted'.
(2) *ASIT Operators*. A general interpretation of the ASIT operators can be proposed:
    - Following the C–K theory, ASIT operators build new *expanding propositions* about C0, which are all of the form: 'there exists C0 and C0 is obtained by the transformation of S through some operation acting on some object of the system'. It is a specific general rule of ASIT to focus on the designs of S' that can be obtained by a transformation of S. This

is consistent with the CWC, which is a property of K. But it also adds in C a strategy of partitioning that could be labelled ‘stay in the (system) box’: a seemingly contrasting strategy with the classic ‘out of the box’ of popular creativity approaches. For a quite fixed system, ASIT allows going out of the (human mindset) box. Clearly, ASIT aims at being creative with the help of incremental changes in the existing system.

- Hence, ASIT operators have to comply with this general logic. Therefore, they can only act on O_i or OR_{ij}, one at a time; and if an object from Ke is introduced, it should be very similar to an existing object in Ks. This set of potential objects that could be introduced can be called Ke*.

(3) *ASIT expanding partitions: a limited algebra for reconfiguration of the system*. Finally, it is easy to match ASIT general rules (with some modifications) with three overlapping categories of tentative expanding partitions in space C. The unification ‘principle’ has been divided into two types to limit the ambiguity of the expression ‘new use’. However, one can easily remark that most rules aim at changing the relations between objects in C.

The expanding partitions are as follows:

(1) Those which act directly on O_i
  - *Object Removal* solves a problem by removing an object from the system.
  - *Unification* (type 1) solves a problem by assigning a ‘new use’ to an existing component where ‘a new use’ can be interpreted as a change in an existing object. This change should be limited to propositions coming from Ks and Ke.

(2) Those which act on OR_{ij}s
  - *Unification* (type 2) solves a problem by assigning a ‘new use’ to an existing component where ‘new use’ can be interpreted as a change in the relations between one object and the rest of the system.
  - *Breaking Symmetry* solves a problem by changing a symmetrical situation into an asymmetrical one.
  - *Division* solves a problem by dividing an object and reorganising its parts.

Again, it is clear that ASIT operators explore a reconfiguration of the existing system with objects that are part of the system or close to it.

(3) Those which introduce new objects ‘slightly changed’ from Ke*
  - *Multiplication* solves a problem by introducing a slightly modified copy of an existing object into the current system.

The above analysis shows that the logic of expansion of ASIT is clearly restricted to small evolutions of existing objects.

In summary, ASIT can be described in C–K constructs as a C–K process built on the following paradoxical assumptions:

(1) A special structure of K: Ks (the system as ‘the box’) and Ke (*a complementary knowledge that is available*).

(2) No K-expansions allowed: e.g. no experience, experts consulting or research process is integrated into ASIT.

(3) The ‘staying as much as possible in the (system or world) box’ principle for space C *looks like on one hand as a strong restriction* of the expansion of C; yet it is also an incentive to maximise the number of expansive partitions that can be generated without changing the objects of the system. Such maximisation exhausts the possibility to be creative with the present system and knowledge before attempting something new.

(4) The generation of expansive partitions is a simple series of permutations and decompositions within the algebra (O_i, OR_{ij}, $PO_{i,l}$, $POR_{i,lm}$, Ke*) with a focus on changing the relations between existing objects.

4.2.2. *Solving the paradox: the creative power of ASIT and its limitations*

Now that we have a formal interpretation of ASIT, it is easier to characterise its paradoxical creative power: it is a process which intends to be creative yet limits the design work to all reconfigurations, whether intuitive or surprising, of the system's objects and their close variations.

Strengths. ASIT offers a systematic way to generate C-expansions without introducing new knowledge or big changes into the system.

- All objects of S should be considered equally, even those that seem *out of the problem* (the acid test example is all about the 'surprising' use of the samples as the protectors of the container).
- All objects should be tentatively removed.
- All objects should be decomposed to see if some reorganisation is possible and finally only new objects that can be used easily should be considered.
- And above all, all relations between objects should be examined critically.

Such systematic generation of a 'reconfiguration grammar' as a source of expansive partitions, corresponds to important challenges in day-to-day engineering where it is not easy and often unrealistic to explore radical changes. It can also favour smart and workable solutions; it can be taught with a clear formalism within or without the C–K theory as the general background. Note that while all objects are considered equally by the method, when practitioners use it, they exercise their professional judgment in determining the sequence of expansions they exercise.

Weaknesses. ASIT has several limitations that are well revealed by the C–K theory.

- *Limitations due to CWC: No complete change of S*: Sticking to existing objects and relations known in the system will inhibit or slow down the design of a complete different system S′, that has none or few objects in common with S, yet introduces only known objects of K. For example, an acid test could be performed by applying very small flow of gas at nano- or micro-levels on the samples so that no harm is done to the macro-container. This proposal is a completely new technology that changes totally the system S. Moreover, concepts generated by ASIT may not be expandable if the CWC holds, for example: putting the acid within the samples may require some technical knowledge about corrosion that is not available.
- *Limitations due to operators' definition*: ASIT operators do not cover all types of expanding partitions that could be suggested by a C–K approach. For example, the C–K suggests the lack of at least two operators:
  (1) *No action on performance criteria*: The new performance to be achieved, FR* is not seen as a target that could be discussed and partitioned. In the acid test example, the damages to the container should be discussed and valued in several ways. Each type of damage may induce a different type of solution (think, for example, on a removable interior of the container that could offer protection for a limited series of tests before being changed).
  (2) *No action on the environment E of the system as an object of the system (a subpart described in Ke)*: the 'container' could be the environment itself: for example, if the tests are done in special wells drilled in the rock (a solution different from a container in specially resistant material).

Due to the above limitations, there are obvious examples of solutions that could not be reached by ASIT. Almost all important processes of industry have been obtained through K-expansions; for example, all the history of time measurement techniques shows solutions which have complete system changes: sundials or water clocks have no object in common with a digital display electronic watch. One can also remark that the introduction of LED-based lighting could not be obtained by an ASIT type creative approach on the electric lamp.

4.3. *Improving ASIT with insights from C–K theory: a stepwise extension of the multiplication rule*

4.3.1. *Revising the CWC in ASIT: restoring K-expansions*

We demonstrated that ASIT steps could be interpreted as restricted C–K operators in C–K spaces.

In this section, we show how C–K can give insights into improving ASIT by restoring the logic of K-expansions. A first improvement of ASIT can be obtained by distinguishing two steps.

- In the first step, the CWC and the method is used as prescribed by its authors.
- Yet, if this first step is not satisfactory, or if resources are available to continue exploring additional solutions, a second step should allow *a limited relaxation of the CWC*, which means an amplification of the multiplication principle which can be reformulated as: 'imagine an object different from existing objects and accessible through Ke that could be added to the problem world performing the wanted action'.

The modification of the 'multiplication rule' is not surprising. It played the role of a gate keeper for the CWC. Actually, allowing the introduction of 'slightly modified copies of objects' was an acknowledgement of some sort of limited 'out of the box' procedure. Now the two steps of an extended multiplication rule can be transformed in a multiple steps procedure where the exploration of wider and wider sets of objects can be explored.

4.3.2. *A generalised ASIT extension procedure*

Finally, in C–K constructs, ASIT and its extensions can be summarised by the following general procedure, which is based on a sequence of openings of the CWC.

Step 1: Select a system S and a desired action A. Consider the concept C0: 'there is a transformation T of S which makes A true'.

Step 2: Build a first knowledge space K0 where all objects and relations of S are included. Build a series of growing neighbourhoods of K (K_0, Ke_1, Ke_2, ...), which may be explored sequentially. (Practically, this sequence could go from easy accessible knowledge to costly and difficult ones.). This approach could be linked to using topological structures for design models (Braha and Reich 2003).

Step 3: (standard ASIT at step i): Generate a partitioned tree of C0 by using any object of S (and any relation between objects in S) as an attribute that can be removed (removal), reused differently (unification and decomposition) or reversed (breaking symmetry); or partition C0 with the help of close objects O' from Ke_i (at step i).

Step 4: If Step 3 (at step i) fails, introduce new objects and relations from Ke_{i+1}, and go to step 3 with an extended problem world S' that substitutes S; or stop if there is no Ke_{i+1} that can be added (e.g. shortage of new objects to introduce).

ASIT as C–K *Linearisation*. This improved procedure can be also modelled as a linearised C–K application. The linearisation comes from the predefined sequence of knowledge extensions

(K_0, Ke_1, Ke_2, …). In the pure C–K theory, knowledge expansions are guided by C-expansions and cannot be predefined independently of the C explorations. But the CWC limits such co-evolution of the C–K and constrains the knowledge expansion. When CWC holds at each step, each concept generated at this step should be transformed into a design solution by only using objects from the knowledge available at that step. While in a pure C–K scheme, any new concept can generate its correlated knowledge expansions.

Example To illustrate the differences between the pure C–K and improved ASIT, let us use again the case of a designer that works on a new watch that has improved precision and cost performance. The existing watch is a mechanical one.

- *In standard ASIT*, the CWC condition inhibits the quartz-based electronic solution: the operator 'removal' applied to the mechanical movement would generate an interesting concept but there would be nothing to replace it in K or Ke.
- *The improved ASIT procedure* offers a better chance to reach it, if electronics is part of at least one of the accessible and predefined Ke_i; yet, if no Ke_i contains electronics, the solution is not reachable.
- *In pure* C–K *reasoning*, the concept of a watch 'without a mechanical movement' is easily generated but the question becomes what type of C–K operator can be built to partition and test this concept. It is important to underline that the absence of electronics in K is not a reason to reject this concept! Moreover, the concept is used as a guide or a trigger for knowledge search: As one can ask 'if there is no mechanical device, what type of phenomena could offer a periodic signal?' And the search process would be oriented, for instance, on natural or artificial oscillators and so on. This search could make direct use of TRIZ effects database.

Clearly, in all these design models, concepts are generated; but the structure of K and the C–K operators are different in each case. Through this comparison, one can remark again that the key issue of the C–K logic is the complete interplay between space C and space K.

In summary, we have shown that:

(1) C–K helps clarifying the purpose and design logic of ASIT.
(2) With respect to the C–K theory, ASIT appears as a consistent and systematic creative method.
(3) C–K helps understanding the implicit assumptions and the limits of ASIT.
(4) ASIT could be extended by allowing stepwise expansion of the problem space/formulation in response to creativity impasse. Such expansions are part of the C–K theory and method.

5. Discussion and conclusion

5.1. *A C–K model of an extendable family of ASIT methods*

C–K has been proposed as a design theory that provides explanatory power on how creativity is possible within a design process; how knowledge could be used to generate new concepts and how design should proceed as the co-expansion of two spaces C and K. The C–K theory, however, does not specify strategies for exploring the spaces when design actually happens. Through its use, different observations could be crystallised into strategies; for example, if some expansion C+A of a concept C, where A is a concept belonging to either C or K, proves false in K, it does not mean the falsification of C and another expansion C+A could become subsequently fruitful. In contrast to C–K, ASIT is a workable creativity method. By casting it in the C–K theory constructs, we have obtained the following findings:

(a) We explain how ASIT may support some creativity in spite of its paradoxical ‘closing of the world condition’: The core idea of ASIT is to offer an easy generation of concepts (expansive partitions) through simple reconfiguration algebra of the system, which are ASIT rules. To maintain workability, the second idea of ASIT is to partition these concepts only with existing or easily available knowledge. Both ideas shape a simple and workable creativity method for ‘in the box’ or ‘near the box’ solutions. From the point of view of engineering, this leads to an important remark: Engineering does not value creativity per se and pure ‘out of the box’ solutions cannot be explored for themselves. Workability, cost, accessibility and time are requirements that bear of engineering creativity. Thus, ASIT may appear as an efficient creativity strategy. However, the limitations of ASIT are the direct consequence of such creativity strategies. Strong C expansions will find no available knowledge and strong K expansions will never nurture the process. Thus, the value of ASIT will depend on how in each design context such trade-off between workability and innovation power is valued.

(b) Using the C–K theory, an improved and extendable ASIT procedure can be proposed. This procedure is based on successive problem space expansions, which correspond to predefined knowledge bases that can be explored sequentially. This improved ASIT method is rather straightforward, and it may be a good interpretation of how people or students use ASIT in practice if they feel too constrained by the CWC assumption or when they first try the method. This proposition could be easily tested by systematic analysis of ASIT practice. Such empirical work could also show how designers spontaneously use *fixed or free sequences of knowledge expansions.*

There are many other creativity support methods that could be explored and modelled similarly. For example, ASIT itself is related closely to two other methods: systematic inventive thinking (SIT) (Goldenberg and Mazursky 2002, Goldenberg *et al.* 2003) and USIT (Sickafus 1997). The concepts of these methods could be similarly described in C–K constructs. In addition, ASIT has been developed based on TRIZ but with the goal to simplify and generalise it. Consequently, the analysis of ASIT and C–K could be extended to these methods.

ASIT is the most succinct and simple methods in the family of TRIZ, SIT, ASIT and USIT. Both SIT and ASIT were created to simplify and make TRIZ more accessible to users. This simplification led to effective methods that are easily taught within a matter of few hours but have the limitations presented in this paper. ASIT’s source, TRIZ, is more complicated mainly because it integrates several methods that are loosely connected and that are highly technical (e.g. the matrix of contradictions among 39 engineering parameters and their proposed rules of resolution). The availability of diverse knowledge sources allows TRIZ to model some K-expansions. USIT, a follower of ASIT, complicates ASIT back partly towards TRIZ, extending the scope of ASIT. In this extension, USIT still maintains the status of ASIT with respect to C–K concepts, partially, because it makes use of the CWC. Such an analysis that exposes the types of C and K expansions that a creativity-support method provides could make predictions about its relative creative power. In this way, the C–K theory provides a way to compare the creativity power of different methods. However, a complete comparison between the C–K and the varied instantiations of TRIZ would deserve special treatment.

5.2. *Towards a scientific and systematic approach of creativity techniques for engineering design*

Recently, Kazakçi *et al.* (2008) introduced the notion of ‘models of C–K theory’. These models correspond to different forms of creative design that are linked to specific structures of knowledge (models of the K space). The generation of such models of the C–K theory can be done using the models of K space available in the literature. An extreme form of such K models can be the Set theory and number theory; Hatchuel and Weil (2007) showed that in that case, the C–K theory was directly equivalent to Forcing, an extremely powerful method for the design of new Sets.

However, the present analysis of a creativity technique like ASIT opens *a different program* that could bring a deeper understanding of creativity techniques which are more numerous and less scientifically explored than K-models. The program could be described as a generalisation of the study done in this paper:

(1) We assume that the C–K theory is a general theory of how creative formulations can take place in design processes through the interaction between C and K spaces.
(2) We assume that any creativity technique can be valuably interpreted as a C–K logic *bounded* by some special constraints such as freezing the structure and objects of C and K spaces; the activity of C–K operators and any other goals imposed on the design process: time, budget, workability, suitability to different type of users, etc.
(3) Such constraints are not necessarily explicit or even consciously built by the inventors of these techniques. But they can be captured and their underlying model will be made explicit through a C–K analysis.
(4) Analyses performed on the major and most contrasting creativity techniques could provide a new theory-driven and systematic approach of creativity methods.
(5) In case we find aspects of creativity methods that could not be described by C–K constructs, we would modify the theory to capture such aspects.

Through careful analysis, we bring seemingly diverging perspectives about creativity to converge to common principles and ideas. We demonstrated that creativity methods like ASIT that evolved over numerous years could be described by the language of a newly developed design theory (i.e. C–K). This allows explaining the advantages and disadvantages of the methods as well as provides support for the validity of the theory. Similar studies will further enhance our understanding of creativity.

5.3. *Towards theoretical analysis of design methods*

We presented a theoretical analysis of a creativity support method and briefly mentioned how the analysis could be extended to other methods, thereby providing means for comparing between them or assessing their creativity support power. The motivation for such an analysis presented in the introduction was the proliferation of creativity support methods and the difficulty to truly understand their essence with other analysis methods. Similar situations exist in design methods in general. The results obtained in this study lead us to propose that theory-based comparisons of design methods in general could be extremely valuable. Such endeavour could provide incentive to develop design theories that would be able to serve as engines for such analyses. The result of this activity would be the fruitful co-evolution of design methods and theories.

Notes

1. This condition means closed object world condition, which should not be confused with the closed world assumption in logic that states that what is currently unknown to be true is false.
2. This is reflected in the deep dive process of IDEO (Kelley and Littman 2001).
3. This is a well-known issue of the legal evaluation of patents. According to most patent laws, an invention must be ‘novel, non-obvious, and have utility’. Novelty refers clearly to what is already known. But ‘non-obvious’ also means that the invention could not have been conceived by someone ‘having ordinary skill in the art’: this criteria needs to delineate what is the ‘ordinary skill in art’.
4. Controllable means that we can find it is partially true or false.
5. This is a tricky question. Initially, Designer 1 might be considered more creative (in ASIT’s view as it stays in a closed world) because she was able to get the desired response without introducing potentially risky components. Designer

2 would be more creative in the long run, because she creates a bridge for more future progress, whereas Designer 1 might have reached the end-result in mechanical watches. This shows that creativity/innovation judgment or measure is knowledge- and time-dependent.

6. Sometimes at lower levels, relations exist between one sub-part and a sub-part of another object. This would complicate the logic but not in principle.

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Nomenclature

C	concept space
CWC	closed world condition
E	environment
FR*	functional goals
K	knowledge space
Ke*	knowledge external to the system but closely related
Ke_i	knowledge neighbourhood close to Ke
Ks	knowledge related to the system
$\text{O}_i, i = 1, \ldots, I$	a finite set of objects
$\text{OR}_{ij}, i, j = 1, \ldots, I$	a finite set of relations between these objects
QCP	qualitative change principle
$\text{PO}_{i,l}, l = 1, \ldots, L$	parts of a system
$\text{POR}_{i,lm}, l, m = 1, \ldots, L$	relations between parts
S	system
$\text{FR}_k, k = 1, \ldots, K$	a finite set of performances (or functional requirements)