A new methodology for advanced engineering design: Lessons from experimenting C-K Theory driven tools

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A NEW METHODOLOGY FOR ADVANCED ENGINEERING DESIGN: LESSONS FROM EXPERIMENTING C-K THEORY DRIVEN TOOLS

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1. Introduction: Managerial expectations for innovative design tools in advanced engineering design

The advanced engineering departments manage design activities of New Product Development (NPD) from idea generation, i.e. the functional and conceptual design of a product, to engineering design, i.e. the embodiment and detailed design of a product. In most innovative contexts, they always face the dilemma of dealing with various design paths and quickly converging on the most competitive one.
To help designers and managers, research in Knowledge Management (KM) and NPD have proposed a wide range of design and strategic management methods. In general, KM tools aim to capitalize and facilitate the knowledge transfer into the organizations, and NPD tools are implemented to facilitate the decision-making processes in order to pursue the best design alternatives. Critical interdependencies between these two processes have been largely mentioned. On the one hand, the failures that may occur in KM process are well known to be also the causes of weaknesses regarding NPD; to such extent that KM has been underlined as a core activity of NPD [Yang and Yu 2002]. On the other hand, NPD gives directions to KM in order to efficiently renew and make the skills of the firm evolve to reach dynamics of customers and market's expectations [Davenport and Pruzak 1998].
Surprisingly, it appears that the fusion of NPD and KM in a single tool is still poorly investigated. The two sets of tools are often dissociated in their use and unfortunately, they lead to several issues largely reported by researchers and practitioners [Yang and Yu 2002].

This article is based on a design theory framework, C-K Theory [Hatchuel and Weil 2009], that models the cognitive design reasoning in situation of innovation. Since its introduction, the principles of C-K theory have been industrially applied several times in order to model and support industrial design processes. In particular, previous research argued that C-K theory could be fruitful in order to explore and structure radically new alternatives during the upstream design processes [Hatchuel, Le Masson and Weil 2004] or to manage the projects portfolio of cross-industry innovation partnerships [Gillier *et al* 2010].
This paper provides insights on practical bridges grounded on NPD, KM and Design theory. Our purpose is to go a step further on the benefits of C-K Theory-based design tools for the management of advanced engineering design.
In section 2, we propose a brief review of the usefulness of NPD and KM tools for advanced engineering design, and we point out some of their limits in intensive innovation contexts. In section 3, we present our theoretical framework and our research methodology. From 2009 to 2011, 14 industrial case studies were

conducted through an action-research methodology by two of the authors. In section 4, stemming from the diverse objectives that cover the innovation process, we propose practical guidelines to use C-K theory driven tools. Then, we point out that such practical guidelines enable managers and designers to simultaneously manage an important amount of knowledge and also to structure the potential design paths of innovation projects. We analyze designers' feedbacks and discuss the benefits for NPD and KM processes. To conclude, in section 6, we propose a few perspectives to further research.

2. Design convergence and sustainability of knowledge: the divergent goals of NPD and Knowledge Management tools in advanced engineering design

2.1. NPD tools: supporting the fast convergence on few design paths

Facing markets that demand more frequent innovative products, but also a drastic reduction of the products life cycle and a necessity to improve their quality, NPD methods and processes have been extensively used and are now considered as key strategic activities. Several statistical studies have shown that the efficiency of NPD is of prime importance to reduce the new products failure rates. NPD literature proposes a wide range of tools for the management of innovative design projects (as *e.g*. Discounted Cash Flows analysis, Analytical Hierarchy Process, Delphi interactive methods, *etc*.) coming from multi-disciplines foundations such as economics, strategy, stochastic simulation, *etc*. (see [Henriksen and Traynor 1999] for a critical review).

Basically, *a large majority of these tools are dedicated to identify problems and to support decision-making* during R&D projects' steering committees: choosing the best technical alternatives in accordance with customers preferences and development costs (Quality functional development, Conjoint analysis, Value Analysis, Value Engineering…), rigorously comparing the performances among different possible technical solutions (Taguchi method, Design of experiment…), assessing the level of risks of design paths (failure modes and effects analysis, …) or managing the right balance and prioritization of projects in management portfolio (Multi-criteria decision analysis, …).

As each next stage of stage-gate NPD processes is more expensive than the previous one, *the great majority of NPD tools serve convergent goals*: they are often deployed to reduce the multiple design path explorations as soon as possible in order to progressively decrease the number of parallel projects. Therefore, NPD tools are often used to schedule the progressive cancellation of less performing options opened by innovative activities. Current NPD methods have been argued to be well suited to incremental innovation, to renew a range of existing products, where the potential of markets profitability, the technical feasibility and costs are well known. However, in cases of radical innovation, symbolized by a high level of uncertainties in both markets and technologies, research studies have also noticed that these same methods are much less suitable [Mc Dermott and O'Connor 2002]. In such situations, the process is often qualified to be emergent, non-linear and not driven by customers but by technological advances. Scholars place great emphasis on the firms' capabilities to explore and create new and heterogeneous knowledge. In particular, it has been shown that NPD scouting process based on traditional criteria of R&D projects' performance (cost, quality, time) does not succeed in supporting efficiently the decision process. Indeed, research show that decision makers do not have to restrict their choices according to traditional criteria but they incorporate several new dimensions of value, as *e.g*. new customers' value dimensions, Corporate Social Responsibility criteria or a new brand strategy. Furthermore, the assessment criteria are not known at the outset but they are created in accordance to the knowledge accumulated during the innovation process. In short, *managing efficiently innovative projects of advanced design engineering seems to be highly related to the firms' capacities to efficiently master their KM process*.

2.2 KM tools: assuring collective learning and the continuity of knowledge

Managing KM is well known to be a key of success of innovation projects. The research community has intensively proposed theoretical models and practical insights to successfully leverage the know-how, experience and skills. In short, KM theory provides a set of tools devoted to *master the sustainability of knowledge*, i.e., to assure that all the valuable knowledge involved during the projects would be capitalized, updated and transferred to all organization members [Davenport and Prusak 1998]. As individuals possess their own knowledge, a main objective of a *KM system is to deploy a systematic explicitness process to support collective learning and ensure the continuity of knowledge among employees* [Nonaka and Takeuchi 1991]. However, in advanced engineering design departments, such objective is still a hard challenge. Our research insists on two main issues to overcome.

A first issue concerns *the codification — i.e. converting tacit knowledge to explicit knowledge that could be usable by people— of the heterogeneous, tacit and fleetingly knowledge that encounters the advanced engineering design department.*

Indeed, most of the existing tools to share and capitalize knowledge require a correct codification of knowledge: for instance, advanced engineering keywords are commonly used in IT search in order that on-going or finished works could be consulted by all members of a same organization. Most advanced tools, as ontological tools, use semantic technologies to improve the codification flexibility and enlarge the scope of search engines abilities. In advanced engineering design, it is frequent that the tacit knowledge is hardly formalized, as it is embedded in designers' brains (*ibid*.). Furthermore, the first stages of an innovation process often encompass more solutions than the solutions embedded in the final products. Such amount of "fleeting knowledge" is thus a critical issue for firms. Knowledge accumulated during an innovative design activity becomes a managerial object in it-self, which needs specific attention to be fruitfully shared and involved in another activity. How to code all the valuable knowledge and not only the knowledge that would be integrated in the final product? How to code and exploit the excess of knowledge in other future projects? The "volatility" of this unemployed knowledge makes it a critical investment for the firm as it is both a strategic and an expensive intangible asset [Pike, Roos and Marr, 2005].

Secondly, even if the knowledge is well identified, codified and available in KM system, such knowledge may be hard to re-use. Indeed, a same knowledge may refer to different meanings depending on the nature of the project; in other words, *knowledge is highly contextualized in innovative design activities*.

The projects of advanced engineering design teams are great opportunities to learn about broad and various domains of knowledge. Such domain may be very new and unfamiliar; the knowledge involved in a specific project is often referred to be hard to understand and re-used by the rest of the firms' members if the condition of the knowledge production is not mentioned. Consequently, a part of the valuable knowledge developed by a firm always risks being forgotten and not promoting. Furthermore, during the activity of innovative design, the degree of validity and industrials' mastery of knowledge — i.e. their ability to resist to variations of context — change during the design process: new knowledge in a situated context could both increase or decrease uncertainty and complexity of the design as new knowledge interact with former knowledge. Besides, this intermediary knowledge distributed among the members of the project team is hardest to explicit and rarely included in capitalization reports and database.

2.3 Research issue: the residual gap of management tools in an innovative design activity

This brief literature review highlights that advanced engineering design departments are trapped in a vicious circle: the innovative design management issues of the NPD management cause great damages on the KM, and, vice-versa.

Indeed, NPD theory gives a large range of tools to support convergence and the development on few design paths but they have weaknesses to deal with uncertainty and complexity. Often, they are not enough flexible to take into account the generation of new value criteria. Such lacks induce strong repercussions on KM. Indeed, NPD approach encounters difficulties to identify and provide new areas of knowledge that could be driven by KM.

Conversely, KM theory offers also a wide range of tools dedicated to knowledge sharing, knowledge capitalization and cross-fertilization regarding old or latest firms activities. Nevertheless, research studies report a few limits concerning the sustainability of the knowledge through codification and

contextualization. Such impediments prevent firms from regenerating new value criteria, and thus, it limits the exploration of new and valuable design path that would be conducted following the NPD principles.
Consequently, a residual gap appears between these two classes of tools: how the knowledge accumulated through KM tools on uncertainty and complexity of a new situation of innovative design could profit to decision-making process on convergent goals of NPD tools? How NPD comparison and assessment process data could be embedded in KM tools in order to guide the learning and to link knowledge to the network of explored design paths?

The purpose of this paper is to discuss the benefits of innovative design tools in order to overcome this residual gap. In the next section, we present C-K theory framework from which methods and tools are derived to overcome the previous issues.

3. Theoretical framework and Research methodology

3.1. Design formalisms from Concept-Knowledge theory (C-K theory)

The theory is based on several propositions that we present briefly before proposing guidelines to fruitfully apply C-K tools in advanced engineering design. The proofs and rationale of these propositions are given in more detail in [Hatchuel and Weil 2009].

3.1.1. Principles of C-K theory

C-K theory is a cognitive theory; it allows modeling the fundamental logic of innovation design reasoning. It is named « C-K theory » as its core proposition is the formal distinction between «Concepts » and « Knowledge ». C-K theory models the design process through interactions and expansions of the concept space (C-space) and the knowledge space (K-space). Exploration in the knowledge space encompasses the mapping of several knowledge pockets that designers activate to understand and progress in NPD process: the K-space gathers all the designers' knowledge (*e.g.*, technical knowledge, marketing studies, laws, standards, and regulations…). A concept (located in the C-space) is defined as a proposition without a logical status in the K-Space; *i.e.* unknown propositions (*e.g.*, ''a guitar without string" or ''a dancing table'') where designers cannot say whether such a thing may be possible or if it would never be the case.

3.1.2. Managerial benefits of C-K theory and industrial practices

Applying the principles of C-K design theory allow designers to model the creative process as the interrelated expansion of these two spaces. The C-space describes the progressive and stepwise generation of 'desirable alternatives'. The list of attributes increases until the description of one of the potential design paths is so well defined that a 'conjunction' between the C-space and the K-space appears. Managers can interpret a conjunction as 'a solution'. On the other hand, the activated knowledge of designers involved in the process constitutes the K-space. C-K theory then sets the framework for a structured and manageable design process based on refining and expanding the initial concept by adding attributes stemming from the K-space or challenging it.
As C-K approach presents a high potential to increase the efficiency of design process, several research programs aimed at implementing tools and creative methodologies from C-K theory (*e.g.* [Gillier *et al* 2010], [Hatchuel, Le Masson and Weil 2004], [Hatchuel, Le Masson and Weil 2009]).

The authors argue that C-K theory gives some insights on how to fruitfully represent design reasoning.
First, the two spaces are separated and have different structures.

- The C-space is a tree of undecidable propositions. Each node of the tree refers to the partitioning (in the mathematical sense) of an initial concept into several sub-concepts. Thus, a design process is modeled by a step-by-step partitioning of an initial concept. Basically, designers envisage different concepts and different possible design paths.
- The K-space is an archipelagic structure. Each knowledge base contains propositions with logical status for designers (*i.e.* designers consider those propositions as either true or false). A

knowledge base includes all designers' skills, learning or experiences.

Secondly, interactions between the two spaces match the particular cognitive efforts that designers deploy during the design process. C-K theory proposes to model them through four operators (*ibid.)*

- K→C: this operator adds or subtracts a property from the K-space as a new attribute of a concept in the C-space. As it allows partitions of an initial concept, this operator expands the C-space with elements from the K-space. From a managerial perspective, it models a step of the description of a design path.
- C→K: this operator seeks to add or subtracts properties in the K-space in order to reach propositions with a logical status. When it succeeds, it creates a "conjunction" which stops the design process. When it does not succeed, the operator expands knowledge with the help of concepts' adjunction, which leads designers in the knowledge acquisition process.
- C→C: this operator relies on the classical rules in set theory that control partition or inclusion. From a managerial perspective, a partition can be either restrictive or expansive. The restrictive partition reduces the space of possibilities without changing the definition or the attributes of the object to be designed. An expansive partition modifies the identity of the initial design object by adding unexpected attributes to the initial concept. It is precisely because of those expansions that breakthrough innovations, including surprises, are possible.
- K→K: this operator relies on the classical rules of logic and propositional calculus that allow the K-space to have a self-expansion, e.g. proving new theorems. For managers, K→K operations describe designers' actions to increase the reliability of propositions in K.

3.2. Research methodology: relevance of the cases sample and data collection process

Our experimentation is based on 14 case studies of innovation design project (see table 1); this research has been led between 2009 and 2011. In order to examine the flexibility of our guidelines, we chose a case study approach in order to investigate a broad diversity of design contexts and industrial areas.

3.2.1. Action research methodology and data collection process

This research is based on the principles of action-research methodology. This methodology enables access to a large set of data and is well suited to qualitative studies as it enables researchers to make sense of the field by interacting and adjusting their investigation. Experimentation was divided into three steps.

- First, four innovative design tools and four practical guidelines based on C-K theory (see section 4 and fig.2) were presented to professional designers and managers. This part was executed through dedicated meetings with industrials and at least two semi-structured interviews with one designer and one manager for each case study.
- Secondly, innovative design tools were experimented through an interactive process between researchers and designers. Two of the authors proposed a first representation of the project to industrials, then, participants criticized it and proposed several modifications. After a few iterations, an intermediate representation emerged and it was used to communicate about the project and the design process in steering committees. In these meetings, three to twenty people were confronted to the innovative design tools; they could discuss the relevance of the representation of the innovative design process and propose modifications.
- Thirdly, a second set of iterations between researchers and designers was implemented to stabilize the C-K representation of the design issue. Semi-structural interviews were led with participants to discuss the strengths and weaknesses of the innovative design representations.

3.2.2. Sampling: diversity of design contexts and design goals

The main characteristics of our sample are the following:

- Various industries: food, automotive, tourism, road safety awareness, ICT, energy and fret transport;
- Various institutions: start-up, SME, large firms, public institutions, and national cluster;

- Various numbers of designers involved: from on leading person to fourteen designers involved in the innovative design process;
- Several levels of innovativeness: from low to high level of uncertainties about market and/or technology.

Four types of C-K tools have been experimented depending on the main design goal of each case study: concept understanding, project management, portfolio management and industry or ecosystem mapping.

Table 1. Sample diversity per main goal of innovative design activity

Main design goal	Cases: Description / Times duration of the action research / Number of designers involved	Levels of innovativeness (degree of uncertainty)	
		Market	Techno.
Concept understanding	1. Nutriset: Building the genealogy of products of a medium-sized firm that develops products for malnourished children / 1 month / 2 designers	Medium	Low
	2. Re-insuring: Understanding design paths of products and services that decrease fears against new technologies / 4 months / 1 designer	Low	High
	3. Two-wheeled Road Safety: Mapping an innovative field on two-wheeled road safety to identify fixation effect and orphan innovation / 9 months / 2 designers	High	High
Project management	4. Electro-magnetic Interference: Developing a disruptive design strategy to take profit of a common defect of devices / 1 month / 2 designers	High	High
	5. Urban Vehicle for one: Concept-driven demonstrator / 9 months / 5 designers	Medium	Medium
	6. Safe Energy: Designing a competitive offer for an Electric mobility market / 2 months / 2 designers	Low	Medium
	7. Off-shore wind-turbine and marine biodiversity: Designing the argumentation for an entrepreneurial project around a good idea /8 months / 4 designers	High	Low
Portfolio management	8. Long Range Electric vehicle: multi-design paths exploration from the closer to ICE vehicle to disruptive paths / 11 months / 14 designers	Low	High
	9. Innovation in fret transport - French transport ministry: Analyzing the innovative field on fret transport and exploring new paths of innovation / 4 months/ 3 designers	High	Medium
	10. Carbonless mobility: Opening new design paths from higher sub-division concepts than usual / 6 months / 11 designers	Low	High
Industry or ecosystem mapping	11. Pedestrian care: Mapping benchmark on pedestrian safety devices / 10 months / 1 designer	High	High
	12. Cluster I-Care - Rhone-Alpes Region: Mapping an innovative field on ICT for autonomy for elderly people to identify fixation effect / 18 months / 2 designers	High	Medium
	13. New energy vectors on automotive market: Describing global carmakers differences / 9 months / 4 designers	Medium	Medium
	14. Biomass and bio-energy: Understanding the bio-energies industry and building a joint innovation program between France and Ukraine / 9 months / 1 designer	High	Medium

4. Practical guidelines and C-K tools

4.1. From theory to practice: presentation of C-K Tools

"C-K Tools" are C-K theory-driven management tools that allow a representation of design reasoning. These tools were experimented by designers and managers interactions during and after their design process in order to support them in the explanation of their design choices and the linkages between the concepts explored and the associated knowledge. The representation of the C-space contains all known or explored design paths. The representation of the K-space gathers firm's knowledge. In innovative design, several managerial goals and managerial actions lead to focus on different types of design paths exploration and selection, and in different knowledge and learning strategies. We invented and experimented four types of C-K tools:

- Concept understanding: To open original design paths, industrials have to describe original concepts and to explicit links with former design paths. The critical step lies in the reformulation of the initial concept to open up creative paths and overcome fixation effects. Basically, this C-K tool supports creativity workshops;
- Project management: To deal with uncertainty and complexity in new product projects, industrials need to identify breakthrough regarding concepts and knowledge. After that, designers use this C-K tool to explicit the variety of options and the keys of design choices. Project representation also includes information on the exploration of alternative design paths that had formerly been excluded but where relevant knowledge was acquired. C-K project representation improves argumentation and managerial levers to negotiate with project's stakeholders on the funding of next steps of the project;
- Portfolio management: To build a coherent strategy, portfolio managers need a mapping of alternative design paths achievable in the firm, relying on a mapping of the firm's skills and knowledge to reach them. They also need information on potential competitors' strategy in the same innovation field. C-K tool allow a joint representation of established firms projects but also of emerging ones or current research activities. The whole representation supports proposals of coordinated sets of R&D projects to gather strategies of learning, partnership and market positioning.
- Industry or ecosystem mapping: To benchmark and monitor industrial ecosystems of an innovation field, designers need a mapping of former, on-going and potential activities of stakeholders. This C-K tool aims to explicit similarities or differences between several firms or institutions' R&D projects, products, services, business models, exploratory partnerships, patents, etc. Explicitness of knowledge highlights the need for skills or new exploratory partnerships to pursue the exploration: this information allows original competitive strategies for industrial firms or original funding strategies for clusters or public institutions.

4.2. Presentation of practical guidelines

Although formal, C-K theory stemmed from practical concerns. It has been developed to help design teams work on highly innovative projects in several industries, providing both reasoning and organizing support. In this section, we present four practical guidelines to increase managerial benefits of C-K tools in advanced engineering design.

1. Adapt conceptual exploration exhaustiveness to your design strategy. The logic of partitioning of concepts depends on the design strategy adopted by designers that [Hatchuel, Le Masson and Weil 2004] called "breadth first" and "depth first" strategies. In industrial practices, time for breadth – *i.e.* to open the exploration to divergent and innovative design paths – and time for depth – *i.e.* to converge and refine a design path – are mostly subsequent. Thus, the use of C-K formalisms could address only one or both subsequently.

First, designers have to define what is their design strategy and then to adapt the exhaustiveness of each partition.

- "Breadth first": a logical partitioning of the initial concept ($C'1= C+A$; $C'2= C+\neg A$) with A an attribute from K-space;
- "Depth first": an enumeration of potential characteristics of the initial concept ($C'_1= C + A_1$; …; $C'n = C + A_n$) with A_1, .., A_n disjointed attributes from K-space (see figure below).

As C-space and K-space are expanding spaces, a partition called "other" must systematically appear to highlight than alternative design path could emerge from future learning.

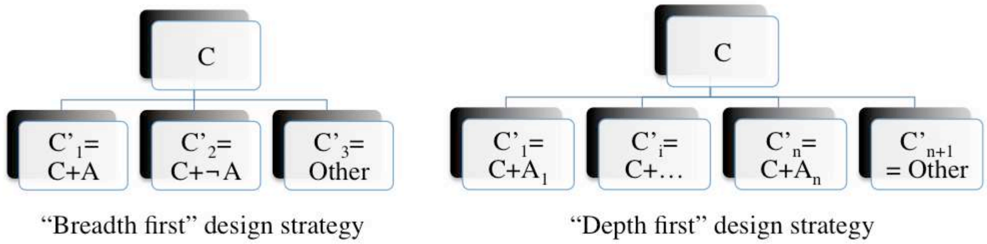

Figure 1. Two different logics of partitioning the C-space according to design strategies

2. Structure rigorously K-Space. As claimed earlier, knowledge explicitness part is often neglected in a design process. Designers must rigorously describe each pocket of knowledge embedded in the design process in order to manage the whole benefit of activated knowledge and in order to be able to reuse it in other design paths. To achieve such a goal, we recommend following the three following sub-guidelines:

1. Each partition must address at least one pocket of knowledge;
2. A base of knowledge much gathers both a description of the knowledge and the associated set of performance criteria. Those criteria allow the assessment or the comparison of design paths engaging this knowledge;
3. Designers have to characterize their degree of familiarity with the knowledge contained in each pocket.

3. Order C-space through increasing levels of breakthrough. The design process leads to different types of concepts, which present various levels of expansions from the known to the unknown. All partitions can be organized according the level of breakthrough that they address, positioning:

1. In the left part of the C-space, the known objects in connection with concepts closed to known and existing objects or services;
2. In the center of the C-space, the expansions that are attainable by an incremental addition of knowledge or a reorganization of the existing knowledge;
3. In the right part of the C-space, the expansions leading to alternative disruptive concepts (not yet explored) and challenging the robustness of knowledge in the space K.

As the C-space is a tree diagram, it leads to a stabilized map structure of all the explored design paths; the current dominant designs is situated on the left side of the mapping and the most disruptive design paths are on the right side of the C-space.

4. Make design regime shift explicit. Rule-based design and innovative design — the two common design regimes— are not managed through similar NPD processes: knowing what design regime is addressed by a reachable design path is an important managerial asset because it allows involving the adequate resources for the exploration of a new concept. Design regime shifts can be highlighted using a color code to account for the degree of expansion of the concepts explored in the C-space (known, attainable, disruptive), and for the degree of familiarity with the knowledge bases (validated, under a learning process, missing) in the K-space. A concentration of known concepts associated to a set of validated knowledge highlights an area where design paths are in or closed to ruled-based design regime. On the contrary, a concentration of alternative concepts associated with a set of missing knowledge underlines disruptive design paths.

Table 2 below is a proposition of the most simple color code that could support this guideline, but of course, it could be enrich through most intermediary levels, for example: in the C-space to separate concepts that the firm could reach alone to those where a partnership is needed; or in the K-space to characterize the progression degree of the on-going learning process. Figure 2 is an illustration of the use of practical guidelines for C-K tools.

Table 2. Design regime color code for C-K tools

		Industrial implications	Theoretical foundations
Levels of concept breakthrough from known to fully unknwon	Known concept	The concept refers to dominant design (i.e. set of known solutions/performance)	Many conjunctions (C->K)
	Attainable concept	The concept is to deepen but it is attainable	Restrictive partition (K->C)
	Disruptive concept	The concept challenges the dominant design - specific project is required	Expansive partition (C->C)
Levels of knowledge robustness from known to fully unknwon	Validated Knowledge	Known and validated knowledge	Stable knowledge base
	On going learning	On-going acquisition of knowledge	Identified knowledge with on-going K->K
	Missing knowledge	Absent or "non-working" knowledge	Lack of knowledge (C->K)

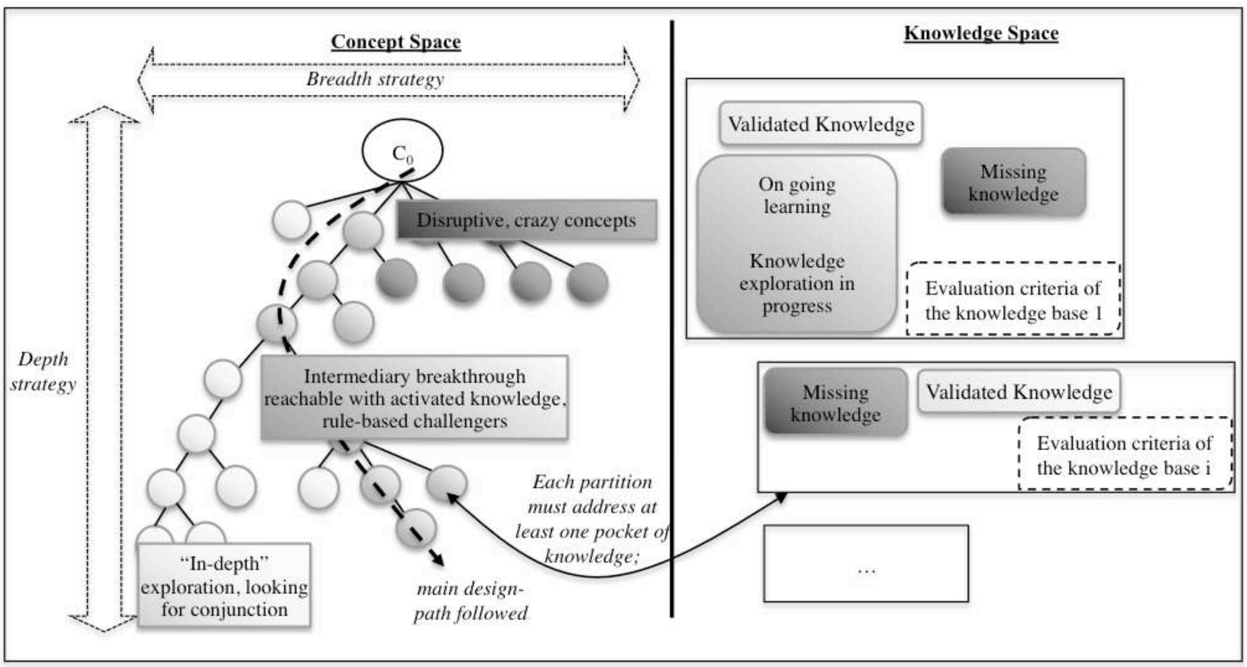

Figure 2. Representation of an innovative design project with C-K Tool and practical guidelines

5. Discussion of the benefits of C-K tools and practical guidelines for advanced engineering design

5.1. Designers' feedbacks on industrial practices of C-K tools and guidelines

5.1.1 Designers' feedbacks on C-K tools

Despite the great variety of case studies, industrials report several common strengths and limits regarding the use of C-K Tools. They underline the ability of C-K approach to structure design reasoning, sustain the opening of original design paths and actively support theirs explorations in NPD process. They also stress that C-K tools allow improving KM in three main dimensions: sharing knowledge among design team members, explaining knowledge reordering and learning to management, and the cross-fertilization of knowledge from one project to another project. However, they mostly complain on the lack of tips and tricks to help designers in C-K practices and a lot of research remains to propose more user-friendly tools. For them, the hardest is to make the correct differentiation between concept proposals and knowledge pockets. Time consuming of K-space documentation was also reported but it appears to be more a global dilemma for designers: the better the systematic explicitness of knowledge is, the better the design robustness.

5.1.2. Designers' feedbacks on C-K practical guidelines

Practical guidelines have been deployed in all industrial cases. Practitioners' feedbacks highlight that this new approach successfully give a procedure to support designers in C-K tools uses. As the steps of the systematic structure of C and K are more detailed, designers could easier schedule their actions to attend design goals. Guidelines force designers to go further into the explicitness of knowledge than the only use of C-K tools. They also support more collective action of design as it involves designers in a constant discussion on the relevancy of the chosen design strategy and allow them to explicit shifts between divergence and convergence design strategies. Industrials also claim that with such guidelines, C-K tools become more managerial and practical tools as it improves their decision making process. Indeed, C-K tools give a whole synthesis of the comprehensive choices made at every stages of the design process. Furthermore, the proposed color codes are said to allow following the design path in more or less abstract level. Nevertheless, some limitations of practical guidelines appeared. First, it is still hard to represent the operators between spaces. Secondly, the generation process of new performance criteria is still unclear and industrials claim that more descriptive guidelines must be given on this aspect, which is really needed for NPD process. However, this issue needs more research, as C-K theory still does not propose recommendations on this point. Third, the on-going learning is still generating new design paths and reachable knowledge but this ability is limited by scarcity of time to explore and of the difficulties to update double space mappings. Dedicated software is now needed to make C-K tools uses more user-friendly, to automate C-K representation and to integrate practical guidelines.

5.2. Managerial implications of C-K theory-driven tools and practical guidelines for NPD and KM improvement

As they propose a systematic structure of design paths mapping and a representation of the knowledge required, C-K tools are effective management tools to improve NPD and KM processes. From our point of view, they actively contribute to managerial stakes of design convergence and sustainability of activated knowledge (see table 3). A few lessons of industrial applications can be discussed.

First, practical guidelines propose a clear method to enhance the explicitness of each separation between design paths (concept nodes) and the knowledge activated by designers to overcome the distinction. As practical guidelines highlight few dimensions of knowledge as familiarity or performance criteria, NPD process' steering committees are better supported. The efficiency of debates between designers and managers on design choices is increased according to deeper descriptions of uncertainties through a better knowledge familiarity, and complexity through a better comprehension of the network of activated knowledge. In addition, C-K practical guidelines consist in providing a method to support the analysis of innovation breakthroughs in the design process of new product. The emergence of expansive partitions could be such a step. These critical moments often call for radical changes in the management of the design process: new skills, new tools for knowledge productions new project management are required. Actually, an expansive partition can change the whole meaning of what has to be done. For example, in the concept-driven demonstrator case study (case 5, cf. Tab1), an expansion of concept made visible new competitive benefits of a more intuitive Human Machine Interface, which has led the design team to make evolve the perimeter of the initial concept. Consequently, the level of breakthrough of concepts and the number of missing knowledge become managerial levers for advanced engineering design. C-K tools and practical guidelines support managers in the active focusing on the targeted design regime (*i.e.* rule-based or innovative design) through different NPD processes. As it allows a joint representation of on-going explorations of several design paths through different design regimes, it helps managers to learn on the

interfaces, and consequently, to manage a more efficient knowledge acquisition and dissemination process among design teams.
Secondly, C-K tools improve the knowledge sustainability as designers explicit the knowledge they activate to overcome a conceptual step. Practical guidelines go further into this explicitness process as they stimulate designers to structure both familiarity and performance criteria of each knowledge pocket. In addition, explicitness of knowledge is extended to intermediary levels of knowledge as the proposed scale of robustness lead designers to also give information on current learning or missing knowledge. KM processes of sharing are very well supported by explicitness of K-structuring guideline, and new keywords for capitalization search engine are efficiently generated through C-based links. These dual movements are linked by C-K formalisms that build efficient bridges between knowledge sharing, capitalization process and NPD management process. This last point enables to address the critical NPD issues regarding the treatment of uncertainty and the assessment of new values.

Table 3 gathers the managerial contributions of each practical guideline to design convergence and sustainability of knowledge goals, and it provides examples of industrial practices where C-K tools could improve the innovative design process.

Table 3. Contribution of C-K practical guidelines to design convergence and knowledge sustainability

C-K practical guidelines	**Design convergence required by NPD**	**Sustainability of knowledge required by KM**	**Examples of industrial practices enhanced through C-K formalisms and practical guidelines**
Adapt exhaustiveness of the exploration to a design strategy	Steering of divergence and convergence phases of the design process	Allow variety in robustness levels of knowledge acquisition	"Depth first strategy" for reverse engineering: understanding the concept beside an object, describing main attributes, associated values and uses of an object, finding its genealogy and articulated dimensions
			"Breadth first" strategy to strengthen an entre/ intrapreneurial speech: project positioning for a contractor on a mapping of innovation paths, building a discourse and decision on such a cartography to share with venture players or internal stakeholders
Structuring K-space	Inform managers on the robustness of the underlying knowledge of a design path	Systematic explicitness of activated knowledge, conceptual links, performance criteria and availability	Steering research (portfolio) and Knowledge Management: proposing a set of coherent actions to provide maximal use of knowledge produced in excess, explaining the levels of exposure to market exit of innovative concepts.
			Piloting a martingale of innovation: building a tiered strategy of acquiring knowledge to commercially exploit a concept as a product line, based on the feedbacks and partnerships from the head of line
Structuring C-space	Enhance managerial information on a design path (breakthrough levels, closed design paths)	Target relevant learning areas and potential use of exceed knowledge	NPD Project management: locating breakthroughs in the design process (in concepts and knowledge), explaining the design choices and learnt knowledge, positioning the alternative concepts documented
			Management of an innovation field: mapping design alternatives, current projects, skills to explore the scope and potential partners of a strategy of investigation of the field
Visibility of Design Regimes Shifts	Adapt the shift from rule-based to innovation design, and vice-versa	Identification of on-going learning and lack of knowledge	Management of creativity: evaluating fixation effects, proposing a re-formulation of a concept and preparing a creative workshop in a targeted conceptual field
			Design of an exploration strategy: mapping of design alternatives considering ability to reach design paths, positioning projects of competitors and stakeholders.

6. Conclusion: learning from industrial practices of C-K Theory in advanced engineering design

In this paper, we go a step further on the experimentation of C-K theory in industrial context and we point out the benefits to NPD and KM approaches. Regarding KM, we claim that C-K Tools facilitate managers to codify and contextualize knowledge mainly because the management of the knowledge is made during and linked to the design process. Regarding NPD, this research shows that C-K tools structure the exploration of unknown design paths and to explicit the links between former and new design paths. We propose practical guidelines that enable practitioners both to control innovative design reasoning and to manage organization of advanced engineering design. The analysis of our results points out that the guidelines permit to improve issues related to KM and NPD in a common framework. Finally, industrial practices underline perspectives for further research:

- K-ownership explicitness could increase information on the availability of knowledge and open potential new ways to represent ecosystem dynamics;
- Representation of time impacts on C-space and K-space dynamics has been excluded of this study despite terms of knowledge availability are crucial information for NPD management.

Furthermore, experiences of C-K tools in industrial contexts outline some new theoretical issues for further improvements in C-K theory: how design reasoning is started and what could be guidelines for choosing the best initial concept? How variety of flows of new information could be visualized to improve NPD and KM processes?

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