INTERNATIONAL DESIGN CONFERENCE - DESIGN 2004
Dubrovnik, May 18 - 21, 2004.

DESIGN 2004

C-K THEORY IN PRACTICE: LESSONS FROM INDUSTRIAL APPLICATIONS

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Keywords: design theory, innovation, design strategies, science-based products, creativity

1. Introduction: the main issues of C-K theory

In this paper we present some industrial applications of a unified design theory. C-K theory has been initially proposed by Hatchuel [Hatchuel 1996] and developed by ([Hatchuel & Weil 1999; Hatchuel & Weil 2002]. It has been presented in detail in [Hatchuel et al. 2003]. It is named « C-K theory » because its central proposition is a formal distinction between «concepts » (C) and « Knowledge » (K). This distinction allows to identify the singularity of « Design » when compared to problem solving/finding approaches or other standard forms of reasoning. The main issues addressed by C-K theory are the following.

1.1 Origins and purpose of C-K theory

C-K theory offers a formal framework that interprets existing design theories as special cases of a unified model of reasoning. This model solves important problems that are not well treated by traditional theories : i) It offers a clear and precise definition of « design » that is independent of any domain or professional tradition ; ii) It gives to « design theory » the same level of rigour and modelling that we find in Decision theory or programming theory [Raïffa 1968] ; iii) It offers a theory where creative thinking and innovation are not external phenomena but the central core of the theory. The latter was hardly addressed in existing theories while Design is obviously a process by which something unknown can intentionally emerge from what is already known.

1.2 Industrial issues in design: Designing in highly innovative contexts.

Although formal, C-K theory was born from practical difficulties. It has been developed to guide the work of design teams working on highly innovative projects in several industries. These industries used to follow design principles close to the «systematic» ones [Pahl & Beitz 1977]. But, these principles were not adapted to radical technological changes and fast evolutions of consumer's expectations. It is in such contexts that we launched a research program aiming to explore new avenues of Design theory and practice. The program was expected to enable a good understanding of early creative phases and to build a *common language* about Design that could be shared at least by the three professional traditions that depend on Design activities : architects, engineers and industrial designers.

1.3 Purpose and main results

The purpose of this paper is to discuss how C-K theory overcomes the limits of traditional design theories and creativity methods in innovative design situations. Using two in-depth case studies, we illustrate how C-K theory overcomes these classical views and presents the following properties:

1. C-K theory supports design reasoning and allows to organise the design process in both innovative situations
2. C-K theory enables to characterize two types of innovative situations which need very different reasoning : *science-based products* (SBP) and *creativity-based products* (CBP). These situations are characterized by : i) the cost and type of knowledge productions ; and ii) the opportunities for "expansive partitions" (see below).
3. C-K theory points out constrated design strategies to face these two types of design situations: we will show how classical notions like "breadth first" and "depth first" strategies can be reinterpreted as ways of balancing the cost of knowledge production and the value of "expansive partitions" in innovative design situations.

Finally, C-K theory avoids two traditional design misleading views : 1-Reasoning within a stabilized set of functions; 2-interpreting creativity in design as an uncontrollable process of idea generation.

1.4 Paper outline

In **Part 1,** we briefly recall the main notions of C-K theory ; in **part 2,** We discuss two case studies showing how C-K theory can be applied in very contrasting industrial contexts. The first case concerns a "science-based product": *the design of new engines for Mars* ; while the second case discusses a "creativity based product": *a smart tool for hammering safely*. In our **conclusion** we will draw some insights on the operational aspects of the theory and orientations for further improvements.

2. Part 1: The principles of Concept-Knowledge theory(C-K theory)

The theory is based on the following interdependent propositions that we present briefly [1]before discussing two case studies[2].

2.1 Basic assumptions and definition of Design

A1. **We call K, a knowledge space,** i.e. a space of **propositions** that have a **logical status** for a designer. This space is always neglected in the literature, yet it is impossible to define design without such referring space.
A2. **We call logical status of a proposition,** an attribute that defines **the degree of confidence** that D assigns to a proposition. In standard logic propositions are « true or false ». In non standard logic, propositions may be « true, false, or undecidable » or have a fuzzy value. A Designer may use several logics. What matters is that **all propositions of K have a logical status, what ever it is.** In the following, we will assume for simplicity reasons that in K we have a classic « true or false » logic.
A3. We call « concept » a proposition, or a group of propositions that have **no logical status in K** (of course all elements used to build the concept proposition come from K). This means that when a concept is formulated it is **impossible to prove** that it is a proposition of K. In Design, a concept usually expresses a group of properties qualifying one or several entities.
A4. Definition of Design : we define Design as the process by which a concept generates other concepts or is transformed into knowledge, i.e. propositions in K**.** The preceding assumptions allow for a definition of « concept-sets » and « concept expansions».

2.2 The space of Concepts : properties and expansions

P1. Concepts as specific Sets: as said before, a « concept » C is a proposition which has no logical status in a space K (i. E. Nor false nor true in K). It says that « an entity (or group of entities) verifies a group of properties Pn ». This definition is equivalent to defining a set associated with C. This set will be called also C.
P2. Concepts are sets defined in Set theory without the « choice axiom »: Having no logical status Concepts are special sets from which we cannot extract one element! This property of concept-sets

[1] The proofs and rationale of these propositions are given with more detail in [Hatchuel et al. 2003])

[2] The reader may also find in the case studies a clarification of the notions presented here in a rather short and abstract way.

concerns a well known fundamental issue in Set theory : it is the problem of the « choice axiom ». Hence, we know from a famous theorem due to Paul Cohen in 1963 [Cohen 1963, 1964] that the choice axiom is independent from the other axioms of Set theory: *hence, we can use all basic properties of sets for concepts while rejecting the choice axiom* !

P3. Hence, Concepts can only be partitioned or included, not searched or explored. If we add new properties we partition the set in subsets ; if we substract properties we include the set in a set that contains it. Nothing else can be done.

P4. By adding or subtracting properties we change the status of concepts : Each time we make an operation like these, we may return to a proposition of K.

2.3 Disjunctions and conjunctions : The design reasoning process

P5. The process of adding and subtracting properties to concepts or propositions is the central mechanism of Design as it transforms propositions of K in concepts C and conversely. We call **disjunction** the process of transforming propositions into concepts (going from K→ C) ; and we call **conjunction** the reverse operation (going from C→K. This leads to more technical definition of design:

P6. Definition 2: Design is the process by which K→ C disjunctions are generated, then expanded by partition or inclusion, to reach C→ K conjunctions.

P7. The tree structure of the space of concepts: notion of expansive partitions : 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 type 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 ;
- 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.

P8. Creativity and innovation are due to expansive partitions of concepts: Concepts can be freely expanded (i.e. partitioned) in the space of concepts, provided that expansive properties are available: These properties can only come from existing knowledge hence from K! Now we have described all the components that are needed to present the Design process that gives the formulation of C-K theory.

2.4 The four C-K operators: the design square

Design can be defined as a process generating **the co-expansion of the two spaces** : spaces of concepts C and spaces of knowledge. Without this distinction Design disappears or is reduced to mere computation or optimisation. Thus the design process is nothing more than the operators that allow these two spaces to expand: each space helping the other to expand. And there are necessarily four different kinds of operators : the external ones : C→K, K→C ; the internal ones C→C, K→K. Let us give some indications on each one. The four operators form what we call *the design square.*

2.4.1 External operators:

- K→C : This operator adds or subtracts properties from K to concepts in C, it creates « disjunctions » when it transforms a proposition into a concept. This corresponds to what is usually called « generation of alternatives », yet concepts are not alternatives but potential seeds for alternatives. This operators expands the space C with elements from K

- C→K : this operator seeks for properties in K that could be added or subtracted to reach propositions with a logical status; it creates conjunctions which could be accepted as « finished designs ». It corresponds to validations in classical design: doing *a test, an experimental plan, a prototype, a moC-K-up are examples of C→K operators.* This operator expands knowledge with the help of concepts.

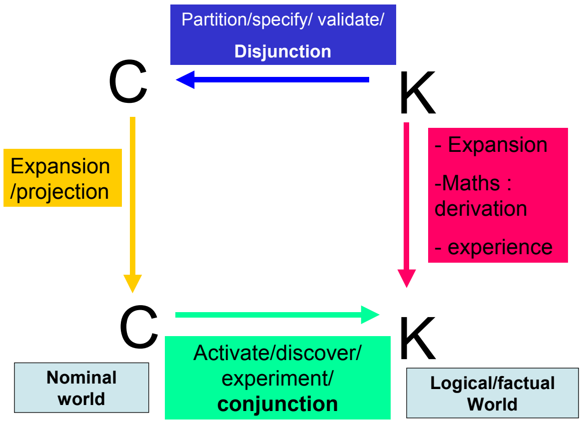

Figure 1. The design square

2.4.2 Internal operators:

- C→C : this operator is at least the classical rules in set theory that control partition or inclusion. But it can be enriched if necessary, provided that Set theory axioms (ZF is enough) are respected.
- K→ K : this operator is at least the classical rules of logic and propositional calculus that allow a knowledge space to have a self- expansion (proving new theorems).

2.4.3 The design square, and C-K dynamics:

Figure 1 shows what can be called the « **Design square** ». It gives the fundamental structure of the design process. It also images the importance of defining Design both on concepts an knowledge.
Another image of the C-K dynamics is given in Fig2. We recognize 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 asks for a travel by some path in C. Designs begins with a disjunction and will end only if some conjunction exists and is judged as « an acceptable solution ».

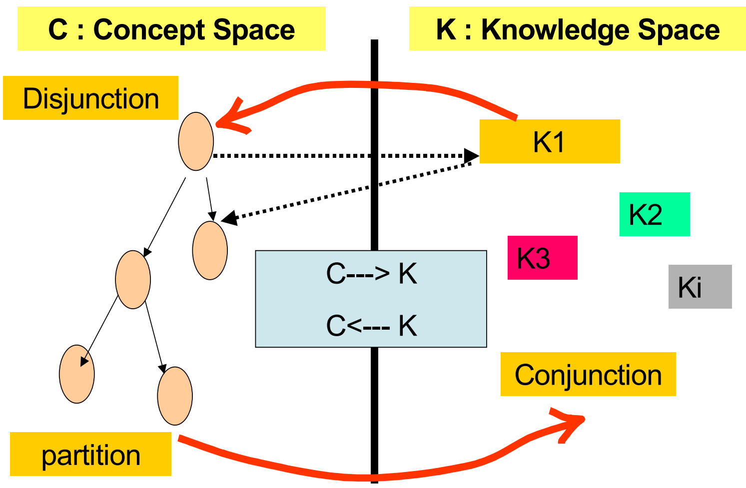

Figure 2. C-K dynamics

We can discuss now the power and applications of C-K theory in cases of innovative design.

3. Part 2. Applications of C-K theory : two contrasting case studies.

We analyse in this section two cases of innovative design where C-K theory was actually used in the design process. The first case took place in a scientific research context where C-K supported C-expansions and helped to open new research areas. The second case appears, at first sight, as an exercice in "creative thinking" where design needs no specific knowledge, yet C-K helps to structure the innovation process in this context. In the first case, C-K helped to *redesign a functional space* and we show that it is based on a "breadth-first" design strategy; in the second case, C-K helped to *structure* a heap of creative ideas and we show that it is based on a "depth-first" strategy.

3.1 The case of a science based product : Mg-CO2 combustion for Mars missions [Shafirovitch et al. 2003]

This first case took place in a European laboratory on combustion ("the lab").The lab works on Mars missions for the European Space Agency (ESA) or the National Center for Space studies in France (CNES). One of these missions was to conduct research on a new combustion system using Martian CO2 as a propellant for a new type of engine. Facing this issue, the research lab director offered us[3] to reflect on the *design strategy* involved in such new combustion system. This was a challenging issue : *to what extent a research program could be considered as a design issue ?* From the point of view of C-K theory, research aims to create K-expansions, yet these expansions should be driven by some C-expansions ; thus, it could help to consider research as an innovative design situation. This idea is well supported by the impact of C-K theory in this project which phases are described below in the language of the theory.

3.1.1 Phase 0: concept emergence from a knowledge base:

It is well known for the specialists that the traditional NTO-MMH propulsion system, a Mars sample return mission needs a huge mass of propellant. This led to a concept of reduced embarked propellant mass. Solutions for reducing this mass consisted either in increasing engine efficiency or refuelling ie find the propellant on Mars. As CO2 is abundant on Mars, it could be used as an oxidant which in reaction with Magnesium provides acceptable specific impulse. A new proposal appeared: Mg-CO2 based engine as a better solution for Mars mission. *Was it a concept?* Yes: it was neither true (we don't know any Mg-CO2 engine), nor false (Mg-CO2 is an exothermic reaction, with an acceptable specific impulse, so we can't say that an Mg-CO2 engine is impossible).

3.1.2 Phase 1: avoiding to be trapped in negative evaluations of a concept:

But how can one work with a concept of Mg-CO2 engine for Mars mission? We needed to add new attributes to the concept. One known type of future Mars mission is *a sample return*. Hence, a restrictive partition of C0 is **C0 + A1 = { {Mg-CO2 engine for Mars mission} (C0) + "sample return mission" (attribute1)}**[4]. With this specified concept it was possible to do a new evaluation i.e. to look for K.expansions (C→K) driven by this concept. Researchers knew how to compare Mg-CO2 with its competitor (traditional NTO-MMH) using a classic criteria: the minimum amount of landed mass on Mars. This evaluation was performed and published in 1996 : Mars landed mass was significantly greater with Mg-CO2 propulsion than with the traditional NTO-MMH propulsion. This result could have put *an end* to the Mg-CO2 concept ! C-K reasoning avoids easily such design traps. C-K modelling shows that such evaluations concern only a partition of C0 ({C0+A1}) but not C0 itself. The proposition "C0+A1 false" doesn't imply "C0 false". So, we have to go back to C0 (4) and

[3] The study was done by Michael Salomon, under our direction, for his final diploma, specialty : "Engineering Design and management" at Ecole des Mines de paris july 2003.

[4] We use the following notation : {xxx} means that xxx is written in C; "yyy" means that yyy is a proposal with a logical status in K.

consider the complementary partition: **C0+ ¬ A1 = {Mg-CO2 engine for Mars mission *not* being Mars sample return}.**

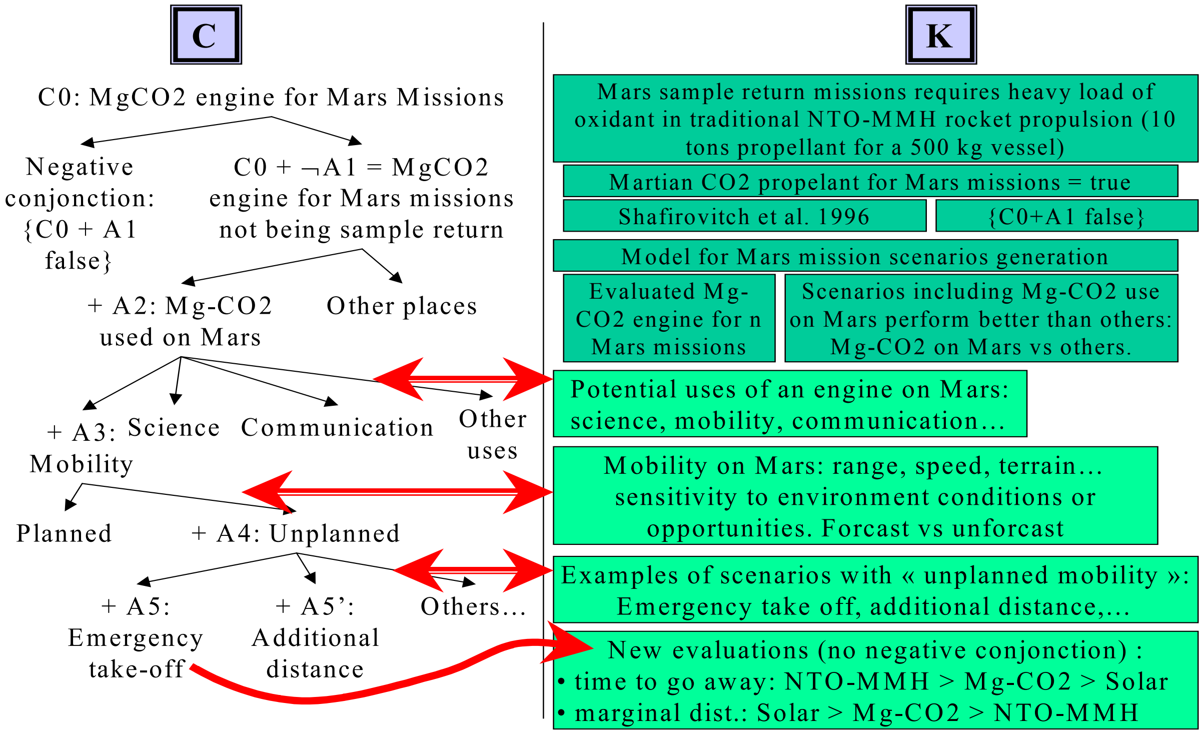

Figure 3. Phase 2-b Mg-CO2; "Breadth-first" exploration

3.1.3 Phase 2: breadth first or depth first expansions : partitioning strategies in C

Now how could we partition {C0+ ¬A1}? One can look for existing mission scenarios and test if Mg-CO2 overcomes other engine technologies. Such study was done by a research team commissioned by ESA and the conclusions where all negative. *Let us show how C-K reasoning helped to rediscuss this study and this new apparent dead-end.* The generation of mission scenarios is a combination of existing parts of the K space. As it is not easy to generate all the possible scenarios, the study choosed to model a family of scenarios with two dimensions :

- *A logistic program* : the mission is defined as an Earth-Earth loop which joins some targeted points of the Mars surface. Various attributes were considered : on the type of routes (surface, orbital, interplanetary,…), on the number and type of vehicles, on their combinations etc. An example: one big vessel leaves the earth, splits into an orbital station and a Mars lander ; the Mars lander splits into small investigation vectors which join the targeted points and come back to the Mars lander ; one rocket is send from the Mars lander to the orbital station and fnally, the orbital station + the roC-Ket come back to the earth. For each displacement one precises the type of engine: Mg-CO2 or NTO-MMH.
- *A scientific program*: it concerns the type of experiments and scientific instruments for the mission.

All scenarios where negative for Mg-CO2. So what was wrong with this type reasoning? This design strategy can be seen as a *"depth first"* strategy. {C0+ ¬A1} was restrictively partitioned with a large amount of known attributes before evaluation. So, like in previous case, no negative evaluation of the partitions could still be negative for the mother-concept C0+ ¬A1! To avoid the new trap it was necessary to return to some early partition. We call it a "breadth first" strategy. And the surprise was that this was now made possible *by the knowledge generated by the negative partitions* ! It appeared that Mg-CO2 performed better in the scenarios where it was *only used for the jobs to do on Mars*. A new partition of {C0+ ¬A1} appeared using the partition: "Mg-CO2 used on Mars" (A2) vs (A2': "other"). And A2 could now be partitioned with attributes *completely different from classic mission* scenarios!

On Mars, the Mg-CO2 engine could be used for mobility, experiments, or communication. Consider the branch *{C0 + ¬A1+"Mg-CO2 on Mars" (A2) + "used for mobility" (A3)},* what are the known attributes of mobility on Mars ? It was easy to find standard attributes in K. Mobility could be range, speed, sensitivity to topography,… Yet, it could also be related to Mars specific environmental conditions. Mars surface is far from flat and is scoured by terrible storms. Being mobile could mean avoiding these bad conditions by flying away. Hence, mobility could be partitionned as "planned" or "unplanned" (A4). And "Unplanned mobility" could be partitionned through "emergency take off" (A5) and/or "additional distance" (A5'). This new partition is an example of ***expansive partition***, ie *a partition that was not a known Mars mission scenario*. Expansive partitions open new range of concept alternatives. They seem "creative", yet **C-K theory shows how they can emerge systematically from a careful modelling of the knowledge expansions and of the design reasoning.**

The evaluation criteria of these partitions was now completely different. It was no more limited to a comparison with NTO-MMH ; it should include a comparison with all energy sources used on Mars, ie solar energy and different criteria. If we evaluate the concept : {C0+¬A1+ "used on Mars (A2) + "for mobility" (A3) + "unplanned" (A4) + "emergency take off" (A5)}.with a criteria like "minimum time to go away" this concept would not be as good as a NTO-MMH engine but would be better than a solar engine (with the variant A5' = "additional distance", the criteria becomes "maximal additional distance" and solar energy is better than Mg-CO2 which is better than NTO-MMH). ***Now Mg-CO2 appeared as an acceptable concept for unplanned mobility on Mars.***

3.1.4 Phase 3: Prototyping strategy and design domains

We had a new concept expansion : {Mg-CO2 combustion for unplanned mobility on Mars surface}. We also had an enriched knowledge base. What was the next design step ? Should one wait for new specifications by ESA? The lab was asked to develop a prototype of Mg-CO2 engines. But what could be a prototyping strategy in such an early phase? What could be learned? C-K-theory helped to distinguish prototyping alternatives and identify related critical parameters. As the interesting concept was {an engine for unplanned mobility on Mars}, the prototype should clarify the competition with the existing rover solution, and Mg-C02 engines should overcome the rover solution for next known missions (ExoMars 2009) (see the partitions on the figure below).

To Design an alternative to ExoMars rover, much more knowledge was available. The Mg-CO2 alternative should at least meet the ExoMars Rover performances: less than 60kg for the engine, less than 180 days for mission realisation, using only 200W available from solar panel, at least 10km range. Yet, what means to design an "Mg-CO2 combustion system" when still so few was known about the engine itself ? However, available knowledge on rocket laws, C02 acquisition efficiency, fuel/oxidant mixture ratio and Mg-CO2 impulse enabled to model distance, time and power as *functions of the masses of CO2 acquisition plant and Mg-CO2 engine*. Therefore it was possible to compute *a design domain* depending only on m_{engine} and m_{plant} (see figure below) : competing with the rover, the Mg-CO2 concept should satisfy the proposition that m_{plant} and m_{engine} belonged to a specified domain. Furthermore, the knowledge about "design domains" meant the existence of degrees of freedom for the formation of a validated design (an infinite but bounded space of acceptable designs) . This stimulated (K→C) a concept of *Design flexibility* that could be partitioned in three types: 1- flexibility on masses for the engine design; 2- Flexibility on performance for the mission designers; 3- Flexibiltiy on masses for mission designers (replace system mass by scientific instruments).

Phase 3 ended with these significant knowledge and concept expansions. *The classic research strategy that aimed to test and enhance Mg-C02 specific impulse was now expanded and structured towards a* *prototyping strategy and a whole new set of mission concepts.* All this allowed at least to open new avenues to a concept of engine that otherwise would appear unduly as having no future.

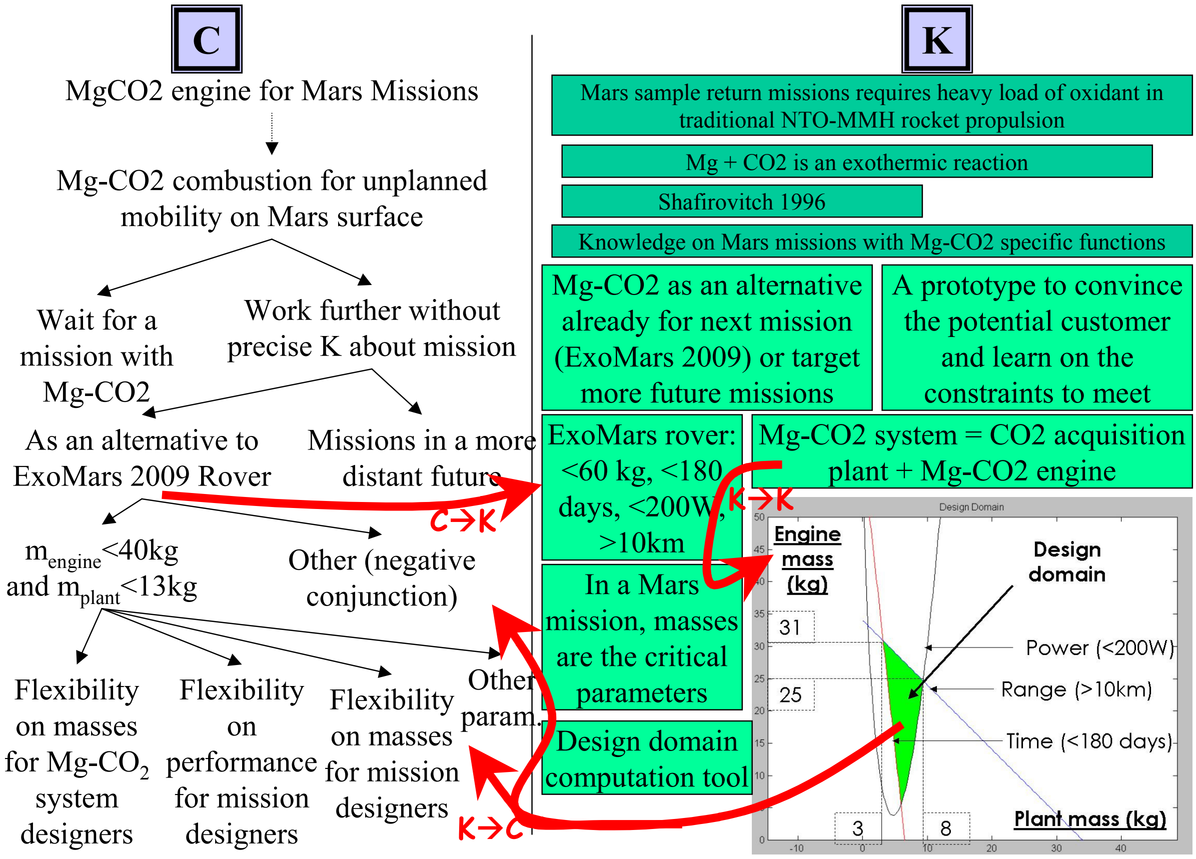

Figure 4. Phase 3 MgCO2: prototype design strategy

3.1.5 Theoretical remarks about case 1: Functions and constraints in C-K

a) In classic design terms, C-K modelling resulted in the generation of a *complete new functional space* for Mars engines. This was a surprise: the first idea was to design an Mg-CO2 engine for a known mission on Mars and the emerging technology should be better than the existing one for this mission. Instead, C-K *reasoning systematically guided the design of new missions that could fit better with the new technology*. This reminds the well known creativity motto of "relaxing the constraints of a problem". But the power of C-K theory is that such creative logic is *completely embedded in the same model of reasoning* than classic design. C-K theory does not distinguish, as in classical views, between the functions (the constraints) and the design parameters (the solutions) : concepts contain both and both are expanded in relation to knowledge expansions. The language of C-K is more general than the "problem solving language" or the "function/ solution" language which now appear as too restrictive for a design theory. ***In C-K, any piece of knowledge is a potential "constraint" (until it is not changed by new knowledge) ; yet we don't know at the beginning of the design process on which concept and for which partition, it will bear upon.***

b) In C-K theory, an innovative design strategy consists in provoking expansive partitions. In science-based products, knowledge production is very costly and uncertain. Thus designers tend to automatically add many well known (restrictive) attributes to initial concepts in order to get confined situations where evaluation and knowledge production is easier This also fits with classic research academic disciplines. As a consequence, downstream phases will be structured as fast as possible by "intensive knowledge" providing many restrictive partitions.

C-K theory expansive partititons are expected in upstream phases. A breadth first strategies consists then in targeting expansive partitions in upstream phases. That's exactly what was done in this case. One can notice that this required an original K production strategies that helped to limit the costs of knowledge production.

3.2 The case of creativity-based products : Smart tools

This second case took place in a start-up, Avanti, looking for innovative products. The first product designed, a nail holder avoiding to hurt one's hand while hammering, was due to a sparkling idea and encountered great commercial success. Therefore, the managers[5] of the company where very interested to find variants or even to maintain the creative level of the nail holder in the design of new products. A challenge for C-K theory.

Figure 5. Avanti nail holder

3.2.1 Phase 1: from breadth first to depth first strategy: knowledge modelling vs trial and error :

When working on a nail holder one is rapidly drowned by *the great number of alternatives*! Hand protection, fore-hole, pliers come rapidly to one's mind. In such case the design difficulty relies less on the lack than on the excess of ideas! Trial and test strategy would be very costly and of limited efficency. C-K helped to structure the universe of these ideas. Paradoxically, in a case where so few knowledge is required, C-K requires to *structure and model existing pieces of knowledge.*

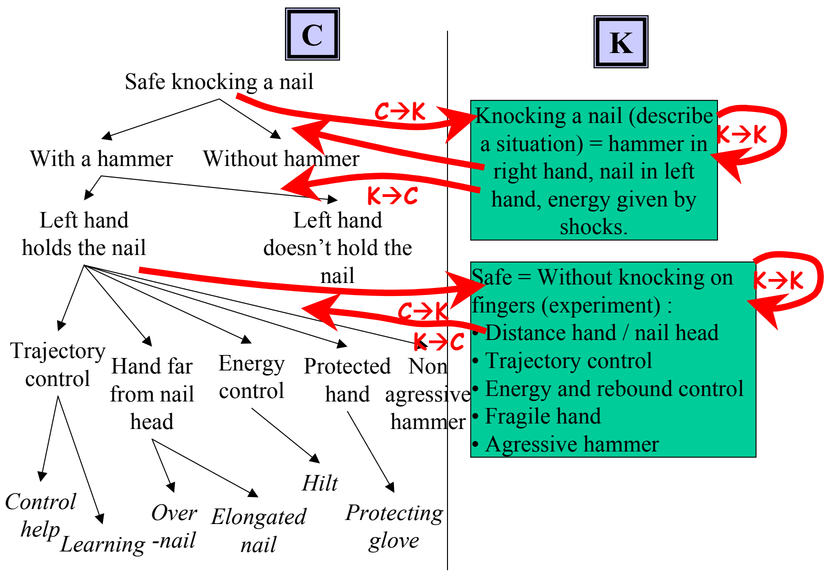

Figure 6. Nail holder phase 1-a

[5] This start-up was managed by some former doctoral students of our department at Ecole des mines de Paris

We present here an example of C-K reasoning that enables to embed the nail holder of Avanti within a larger set of expansions. C0 = {safe knocking a nail}. One goes to K and activates knowledge on "knocking a nail". How can we partition it and avoid shortcuts ? Several ways are possible : avoiding the hammer or finding solutions where the left hand still holds the nail. In fig. 8 "nail-holder phase 1-a" one finds a partition of {C0+"with a hammer"+"left hand holds the nail"}, this partition distinguishes sources of accidents in traditional hammering. **We also identify Avanti designer's expansive partition** : the branch {the left hand doesn't hold the nail} which appears immediately in C-K modelling. Yet, to evaluate this concept it is necessary to model in K the role of the hand that holds the nail. (see figure nail holder phase 1-b). Finally, in this phase C-K reasoning structures the heap of alternatives that inhibits spontaneous creativity.

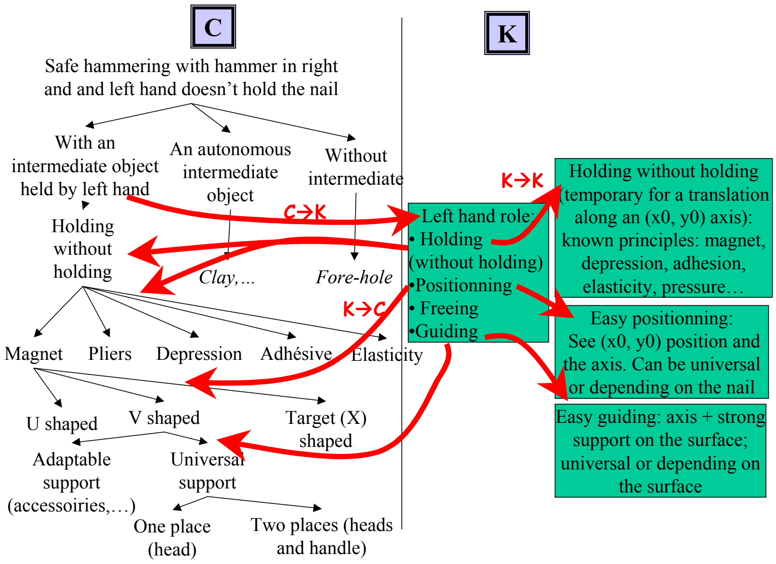

Figure 7. Nail holder phase 1-b

3.2.2 Phase 2: interpreting market knowledge into a larger concept: smart tools for do-it-yourself products

A second use of C-K-theory consisted in interpreting market informations: after the nail holder success, what could be the follower? A safer nail holder? A more accurate nail-holder? An up-market nail holder? Should one pay for a market study about usage and valuable improvements of nail holders? Should one even try a new "breakthrough" in do-it-yourself-market or in another market?

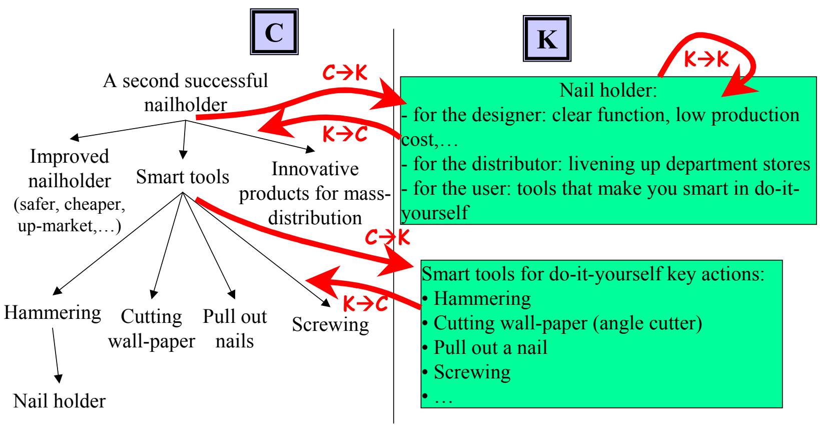

Figure 8. Nail-holder phase 2: from nail holder to smart tools

This is the traditional alternative between systematic design (improving functions, conceptual models, embodiments,…) and creativity (ideas coming out of the blue). C-K helped to find a third way between both. *It consists in considering the "nailholder" not as a tool but as a concept of product like one says 'blockbusters" or "stars"* . Hence the concept : {product of the nailholder-type} was explored with C-K reasoning. New attributes appeared when existing knowledge about do-it-yourself products was collected. And finally, what was designed was... *a design strategy called "smart-tools",* a class of tools being still easy to use, cheap to produce, smart in design (expansive partitions) and livening up departement stores. It gave birth to a whole range of tools that sustained the growth of Avanti. Thus, C-K theory supported the structuring of design not only for one new product but for *a growth strategy*.

3.2.3 Theoretical remarks about case 2: revisiting creativity

a) In classic terms, we were facing here a large heap of creative ideas. Usually, it is recommended to perform some "idea screening" approach trying to assess feasibility or market potential, with a lot of uncertainty or a lot of costly investigations to test all candidates. C-K theory leads to think differently. It helps to "control creativity" : i.e. to identify quickly the relevant set of expansive partitions.

b) This work implied a very challenging design strategy: in such design situations a spontaneous trend consists in using available knowledge (on usages, on existing ideas…) and this leads to restrictive partitions for a "breadth first strategy" (the classical out a brainstorming style work). Instead C-K reasoning guides to a "depth-first" strategy which is the only possibility to identify expansive partitions ("holding without holding" do not appear in early partitioning steps); this requires paradoxically an intensive modelling work in spite of the seeming simplicity of the existing knowledge (what is "hammering" seems quite obvious unduly...).

4. Conclusion: learning from applications of C-K Theory

In this paper, we analysed two cases, the first being science-based, the second rather "creativity" oriented. We underlined how C-K-reasoning *models with the same unified framework* such contrasting designs situations. It also helped to avoid the traps that usual reasoning, be it systematic design, or problem solving approaches, would have induced in such cases. We also showed how C-K modelling systematically explores new alternatives. We will now synthesize the main contributions of C-K theory for both : i) design reasoning and ii) design organizing and management.

4.1 Controlling and expanding Design reasoning

4.1.1 Guiding the expansion of Concepts and knowledge

C-K clarifies the different design situations between the two contrasting cases : SBP requires major conceptual expansions (ΔC) and major knowledge expansions (ΔK); while CBP requires rather major conceptual expansions (ΔC) and minor (even near zero) knowledge expansions (δK).

- ΔC examples : in the first case C-K helped to transform the concept of "Mars missions" through the exploration of Mg-C02 engines and avoided the reverse operation which is the classical design view in engineering. The same reasoning model also helped to formulate the new concept of "smart tools" in the second case.
- ΔK or δK examples : in both cases, C-K compelled the designers to describe and model their existing knowledge (modelling mission scenarios, modelling the role of left hand for holding a nail,…). And this *allowed to identify the parts of this knowledge that had the best partitioning power*. Moreover, any ΔK is a potential contributor to several new conceptual expansions that can be identified thanks to the reasoning model. Finally, knowledge has no value *per se* in design, it takes a contextual value when it helps to expand one or several concepts.

4.1.2 Guiding the elaboration of C→ K and K→ C operators

Evaluation of alternatives: C-K enabled to control the evaluation activity (to know what concept was precisely tested).

Revisiting the classical opposition between Knowledge exploration and exploitation [March 1991]**:** In C-K theory Knowledge exploitation has a clear meaning : using some existing proposition in K to partition (K→C) or to validate (C→ K). Yet, Knowledge exploration seems a less clear notion if we don't specify what type of exploration we are dealing with. In C-K, the search for new knowledge is dependant of the formulation of expansive partitions. So, the natural logic of the balance between exploration and exploitation could be challenged.

- In SBP products the important amount of existing knowledge tends to favour exploitation which means a "depthfirst strategy". Yet, this strategy will minimize the possibility of expansive partitions or these will happen late and at a detailed design phase. In the Mg-CO2, case C-K helped to avoid that trend an favoured an early expansion of concepts and knowledge.
- In CBP products, the natural trend is to generate easy expansive partitions very early which correspond to an "exploration" strategy justified by the lack of existing knowledge. But these expansions become too numerous and their partitioning requires and ever growing need of knowldge. C-K guides towards the other direction. A "depthfirst" strategy allows to make a new use of the existing knowledge. Instead of looking for alternatives to "hammering", what we know about hammering is detailed and used in different combinations. Expansive partitions will appear after several steps of partitionning: but they convey strong and surprising propositions.

Finally, it appears that the classical distinction between exploration and exploitation was built upon an implicit design theory that was not clarified. Exploration and exploitation should be considered as having no general meaning, and can be operationalized and clarified only contingently to an explicit design theory.

4.2 Guiding Design organization and management

Perhaps one of the main contributions of C-K theory consists in *clarifying tasks and teamworking* in upstream or innovative design phases. It helps to analyse critical turnpoints in the design process. The emergence of some expansive partitions could be such turnpoints, and these critical moments often call for *changes in the organization of the design process* : new teams, new tools for knowledge productions, new project management could be required. Actually, an expansive partition can change the whole meaning of what has to be done. An "engine" project can suddenly become a "mission design" project, as did Mg-CO2. These critical moments in the organizing of design has been discussed extensively elsewhere [Holmberg, Le Masson, & Segrestin 2003]. This confirms that the organizing of a design process is not the settling of one organization, but the building of a sequence of transient organizations. And managing design can be more accurately defined by the necessity to manage such transitions. This idea has be developed in the field of the management of innovation as a complementary approach to classic project management [Hatchuel, Weil, & Le Masson 2004].

4.3 Further improvements in C-K theory

Experiences of C-K applications in an industrial framework outline new theoretical issues. It appears that different C-K-strategies are possible and more or less fruitful. *We have seen how a "breadth-first" strategy is consistent with SBP, while "depth-first" strategy is consistent with CBP*. This paves the way to a more detailed analysis of the different C-K-strategies. At this stage, C-K theory is still a pure reasoning theory, further developments will introduce more selective principles for design strategy generation.

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