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TEACHING INNOVATIVE DESIGN REASONING: HOW COULD C-K THEORY HELP?

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ABSTRACT
How can we prepare engineering students to work collectively on innovative design issues, i.e. ones that are usually considered as ill-defined, "wicked" problems? Engineering science teaching has to be completed by some experience of design. Project-Based Learning (PBL) has long been seen as a good way to learn design although it is also recognised that it has to be backed by knowledge on design thinking, to help focus on the *critical* learning issues. Historical cases in creative engineering and industrial design teaching show cases of "project-based *critical* learning" (PBCL) where PBL was in fact supported by clear design thinking with three common principles: acquiring strong (disciplinary) knowledge, learning to be ready to produce knowledge, learning to design in unknown situations. C-K theory, a recent theory of design reasoning which accounts for creative design, models the design process using existing knowledge, expanding knowledge bases and exploring unknown concepts. Hence it provides relevant knowledge on design thinking to support teaching of innovative design. We illustrate the use of C-K theory, first in an interpretative way, to reveal active knowledge expansion in creative projects; and second as a methodological tool to support the design of smart shopping carts.

Keywords: creative design teaching, project-based learning, C-K design theory

1 CONTEXT: NEW ISSUES IN INNOVATIVE DESIGN

There is a growing need today for innovation and creative engineering. Increasing the pace of innovation is no longer enough. Companies try to routinely provide radical, disruptive innovation, and to strengthen their innovative design processes. Engineers have to modify their design reasoning and also to collaborate with other creative designers such as industrial designers, architects, artists or even the end users. They not only apply their competencies in engineering sciences but also work with other knowledge creators. How can we prepare engineers for such innovative design issues?
First, we will show that a new design theory, such as C-K theory, can help teach creative design in what we call a project-based critical learning process (PBCL). Second, we will illustrate this C-K based PBCL with two teaching cases.

2 BESIDE ENGINEERING SCIENCE, BEYOND PBL: DESIGN REASONING TO SUPPORT PROJECT-BASED CRITICAL LEARNING

2.1 The need for project-based critical learning in creative design

At stake is the way engineers deal with "ill-defined" [1], or "wicked" [2] problems. This is radically different from classical optimization and modelling; the new reasoning enables designers to collaborate with other designers who apparently reason in a very different way. Teaching common, innovative design reasoning requires more than just adding a new science to the engineering sciences [3]. Issues related to design reasoning have already arisen in the history of engineering design education: they have regularly provoked dramatic changes in engineering education [4].

Today, these issues have been addressed by complementing engineering sciences with "project-based learning" (PBL) (capstone or cornerstone), to make engineers apply their knowledge (in a creative way) [5]. However PBL has certain limits [6]: limited creativity, difficulty with evaluation [7], strong demands in terms of coaching, little relevance regarding innovation issues due to limited knowledge creation, and poor exchanges with industrial designers or architects.

Recent debates on PBL [8, 9] show that PBL is actually a "scaffolded" process, relying on expert guidance, based on "particular reasoning strategies" [9]. Hence, teaching innovative design requires a better understanding of design thinking [6]. A theory of design thinking would be extremely useful for design teaching: it could be taught and learnt in a relatively short time, in controllable processes, with evaluation and exercises to improve creative efficiency.

A design theory provides a means of organizing *the learning process* and *orienting it towards the most critical points* to be learnt. Based on a design theory, it is possible to organize what we propose to call "project based critical learning", which consists in: 1- teaching a design theory that can be related to critical cognitive and organizational issues; and 2- organizing, on this theoretical backbone, a curriculum that encompasses classical teaching (i.e. the. disciplinary content in engineering science) and projects.

This process combines the advantages of classical PBL (collective experience of ventures into the unknown, motivation, real life or quasi-real life situations, etc.) and the advantages of theoretical approach (offering an integrated framework, supporting the discovery of complex and non-intuitive reasoning, avoiding student manipulation by enabling discussion and criticism of the process, etc.).

2.2 Some historical examples: requirements for a theory supporting PBCL

What is expected of a theory of design thinking aimed at supporting creative design teaching?

There are already cases of "scaffolds" for PBL in (innovative) design education. In the *industrial design* tradition, the education program of the Bauhaus school is one striking example [10]. It was based on strong theoretical works by Gropius, Itten and others In his introductory course, Itten did not follow the classical teaching pattern of the Beaux Arts (copy the models) but taught "the fundamental laws of colors, forms, composition and creation" (p.31). Students then had to do three types of projects: studies of nature and materials, analyses of old masters (such as the Issenheim Altarpiece), and nudes. He taught a grammar of shapes, colors, contrasts, rhythms, and materials, showing the different materials' essential and contradictory aspects.

Engineering design has also done a great deal of work on the PBL "scaffold" issue. One archetype reported by König [4] is Peter Klimentitsch von Engelmeyer (1855-1939), a Russian-German engineering design professor and theoretician who proposed the first integrated engineering design theory that linked intuition and knowledge creation into a design process. Klimentisch built a "Theorie der kreativen Arbeit" (1912) (see also [11]) and deduced from it a scaffolded process of project-based learning. He defined three types of projects, which can be characterized by different levels of expansion: designing a variant of an existing machine (a computing problem only), improving a function of a machine (applying scientific knowledge when the main working principles

are known) and new construction (an Edison-like project, requiring the investigation of new physical principles to address emerging needs).
Even if they address different types of designers, both teaching processes are structured by a type of design reasoning and they share three common principles: they insist on knowledge acquisition (grammar of shapes, study of old masters, reverse engineering, etc.); they underline the limits of existing knowledge (exercises to explore new combinations of shapes, colors and materials, projects to improve machines or even to explore new phenomena, etc.) and they train students to face unknown design situations (Bauhaus teaching program, Klimentitsch's innovative projects).

2.3 Project-based critical learning with C-K theory

Bauhaus led to industrial design teaching ; Klimentitsch' method to; engineering design teaching. Pahl and Beitz [12] and the recent history of engineering teaching [3] are more recent examples of this second lineage of works. These teaching curricula have recently been confronted with the issue of teaching more creative design [13, 14] and have at the same time tended to become increasingly interrelated [15]. This requires a unifying theory of design reasoning to support effective PBCL: Dym & al. call for a design theory mixing divergent and convergent thinking, to be able to teach divergent-convergent questioning [16, 17]. Such a theory should account for the use of existing knowledge, the acquisition and generation of new knowledge and creative reasoning on new design concepts; it should also be "unifying" (valid for engineers as well as industrial designers). They refer to C-K theory as a valuable candidate.
C-K theory [18, 19] was initially developed to support innovative design teaching. We shall now see how it meets the requirements of an innovative design theory. Defining K as the space K containing all established (true) propositions (the available knowledge), a C-K design process begins with a proposition which is undecidable in K (neither true nor false in K) about some *partially unknown* objects x. Concepts all take the form: "There *exists an object x, for which a group of properties P1, P2, Pk are true in K*". All design projects intend to transform an undecidable proposition - *their "brief"*- into a true proposition of K by adding new properties to C which come from the space of knowledge K and by producing new knowledge guided by conceptual issues. These partitions of the concepts can be either restrictive or expansive. If the partition expands the definition of an object with a new property, it is called *an expanding partition*. Conversely, if the partition relies on an existing definition of the object, it is called a restricting partition (speaking of "a house with a red roof" is a restricting partition if "houses with red roofs" are already known in K).
As in the cases of Bauhaus and Klimentitsch, C-K theory combines the classical engineering design emphasis on *knowledge* and *knowledge creation* with the creativity requirement to *venture into the unknown* (C0) and break the (right) rules to create new, *original* artefacts (expanding partitions) [20-21].

3 TWO CASES OF CREATIVE DESIGN WITH C-K THEORY

To illustrate the role of C-K creative design teaching, we will first study a case of PBL (without C-K scaffold), where C-K is used afterwards as an interpretative tool to underline the difficulties of creative design; in a second case we use C-K in a PBCL context to enhance the creative and innovative power of a team.

3.1 Case 1: revealing the active K expansion in creative projects

This case was conducted as a joint program of a school of Art (ENS art de Nancy), a school of engineering (ENS des mines de Nancy) and a business School (EM Nancy).

During one year, groups of four to eight students from the three schools were asked to lead innovative projects of various types. To assess the educational and creative aspects of the projects, six of them were studied by an educational psychologist, Robert Plety, and a professor of engineering, Claude Crémet, using several empirical materials (video recording, etc.). C-K theory was selected by the team as a framework to assess the "creative" aspects of the students. The main findings are as follows:

- *Concept formation and expansion*: the students tended to call "concept", not the first design brief, but the "feasible project goal", derived from the brief agreed upon by the group after its initial intensive discussions. Hence, the role of space C was entirely implicit and there was no formal building of a set of concept variants with several degrees of elaboration. Nonetheless, the notion of "concept expansion" describes the students' activities very well.
- *Knowledge activation and generation*: the elaboration of the concept was obtained through intensive activation and generation of new knowledge.
- *Two distinct project phases* of co-elaboration and co-operation: the project followed a first phase of "co-elaboration", characterized by intensive discussion, knowledge expansion and the generation of the "feasible project goal". This can be interpreted as the phase of creative design. The second phase, "cooperation", corresponded to the progressive elaboration of the concept, in which the work was divided out according to the students' curricula: engineering students behaved as engineers, art students as artists and business students as managers. Thus the project came closer to a development program. It was clearly observed that it was only during the creative design phase that all the students behaved very similarly and it was difficult to see who was following which curriculum, *as if the logic of creative design were a universal logic, common to all professional traditions*.
- *Informal conceptual expansion:* this first case offers strong support for C-K theory, which proves to be a consistent, revealing theory of creative design in educational projects. However, it was also observed that "spontaneous" creative design tends to reduce, oversimplify or neglect the structuring of C. Hence we can formulate the proposition that spontaneous creative projects tend to have an *informal* conceptual expansion which may limit their power of novelty and value.

3.2 Case 2: designing a "smart shopping cart" with C-K theory

In a second case, a group of students trained in C-K theory used it to design a "smart shopping cart". The only available source of new knowledge was a free Internet access. The work was done in a very limited time of 2 hours *as a severe test* of the power of the method. This experiment was done eight times with groups of four students from engineering design, industrial design and management studies. It is important to indicate that the students were not told to be "creative" but to try to build the greatest number of expansions in both C and K. The final results were to consist in complete C-K diagrams and not simply a concept or a list of ideas. Novelty and value where assessed by comparing the variety of the students' proposals to an Ideo experiment broadcast by ABC News in 1999 using the same brief. The broadcast was unknown to the students. The following summarizes the main observations made and focuses on the contrast with case 1.

- Use of the method: the case of Space C. In spite of its abstract nature, C-K theory seemed to be easily accepted by the students. However, in practice, the students always spontaneously focused on discussions in space K and failed to structure space C. The coaches had to intervene in order to refocus on a thorough structuring of Space C. When compared to case 1, it is interesting to find the same spontaneous behaviour which tends to neglect working directly on the conceptual alternatives which are precisely the source of expanding partitions, as if the students believed the common idea that analogy, metaphors and "good ideas" are produced by pure serendipity. Once asked to clearly model space C, the students were themselves surprised by the power of the partitions generated by the simple interplay of the mechanisms.

- Broader exploration in C: the mandatory use of the dual expansion process systematically generated a wide range of novel and surprising ideas in which the notion of the "cart" was greatly enlarged and finally questioned in some cases, far more than in Ideo's standard creativity process. To mention two examples:
- Example 1- The concept of a "smart shopping cart" was repeatedly expanded by adding a new display device to the cart for offering services such as information, navigation, help or advertisements. However, existing knowledge on the tough conditions suffered by carts (outdoor storage, multiple shocks, loads, etc.) tended to increase the cost of the display and threatened the concept. The idea was usually either simplified or abandoned. This is an effect of poor development in C: the display was immediately considered as an attribute of the cart, which was considered to have a set definition in K. Asked to use C-K completely, the student had to model all that they knew about "displays" in K; this revealed the obvious fact that most shoppers already have a display device in their pockets (cell phones,PDAs, etv.). Displays then appeared as an attribute of the users (expanding partition) not of the carts. Consequently, it was logical to partition the "smart shopping cart with a display" concept into two new concepts in C: the display belongs to the users or to the cart. Evaluating the former concept, almost all the issues about the display disappeared and a new class of interfaces emerged between the user and the supermarket.
- Example 2. Redesigning the supermarket. When students were asked to take into account that shopping on the internet needs a "virtual shopping cart" they began to build a new variety of combinations and hybrids in C, between the Internet shopping process (the shopper chooses at home and purchases are delivered at home) and traditional physical supermarket shopping (the shopper chooses in the supermarket and brings purchases home). In these combinations, expanding partitions systematically appeared, offering different, new identities for supermarkets, like reinventing the showroom with a cart reduced to an intelligent recording device (the shopper chooses in the shop but the purchases are delivered). In this way, structuring C could lead from a smart shopping cart in a classic supermarket to smart supermarkets with appropriate shopping carts!
- C-K as a systematic method for innovative design: Finally, case 2 strongly supports the idea that the creative process which aims at novelty and value corresponds to a systematic type of reasoning which is correctly captured by C-K theory. Training the students in this type of reasoning helps avoid any special reference to strange creative processes that produce ideas that come from nowhere, without any clear process. Moreover, students are often sceptical about the level of novelty they can attain on their own or through a "creative effort" on their part. Once they have been convinced by the power of C-K theory, they usually feel much more at ease when they have to face an innovative project.

4 CONCLUSION

This paper showed that creative design teaching would benefit from a PBCL method, that such a method could be supported by a theory of design thinking and that C-K theory is relevant to the process as it focuses on C for a longer period of time and supports the variety and originality of collective exploration by engineers and industrial designers.

It paves the way to an evaluation of the method through experiments and to its improvement by varied exercises, addressing more specific issues (design organization, user involvement in the design process, design reasoning and engineering science education, etc.) and more structured curricula (progressive exercises to support creative design learning).

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