A model of cognitive activities in design

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A MODEL OF COGNITIVE ACTIVITIES IN DESIGN

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ABSTRACT: *This paper presents a model for cognitive activities during design. Design is considered to be a process of cognition construction. The paper aims at identifying mental activities of the designer. Through these cognitive activities, addressing a series of themes, the designer carries out design using the resources that are available to him. The model allows a better understanding of the design process and may contribute to a future general theory of design. After the introduction, the paper describes the underlying problem, refers to a series of interesting contributions of the state of the art , presents a model for cognitive tasks and shows what are the characteristics of design, considered as a specific cognitive task. The concepts are illustrated and finally, the implications of the model are discussed.*

KEYWORDS: *design theory, cognitive theory, working memory, semantic memory, mental representation.*

1 INTRODUCTION

1.1 Background

This paper has been prepared in the context of research on design theory. A previous paper (Huysentruyt & Chen, 2010) acts as a starting point. The present paper is the result of a multi-disciplinary collaboration between researchers in engineering and in cognitive science. It is an attempt to relate findings and theoretical contributions of cognitive science to design. Design is analysed from a designer-centred perspective. Conversely, design constitutes of goal-oriented application of concepts and other elements of cognitive science.
The exploration of the relations between cognition and design is far from complete and hence, the paper has to be considered as work-in-progress.

Deconstructing design
Design is a very complex phenomenon and the diversity of specific design instances in all kinds of projects is ended-less. During the above-mentioned research on design theory, special attention has been given to try to identify the groups of elements that determine design. These groups of elements or variables pertain to:

- *The project*: very often, design is a part of a project that leads to the realisation of an artefact. Hence, the project acts as the operational context for design. The project, if completed, leads to the realisation of one or more artefacts that fulfil the project intent.
- *The artefact:* by definition, artefacts are objects that are not found in or generated by nature. Unless they can be made at once, without explicit reflection, they are the object of design. They are extremely diverse, ranging from physical products, symbolic objects (for example, a totem or an obelisk) and to virtual objects that have to be animated (like a web page or a movie) or executed such as computer programs or a business process.
- *The design process*: by definition, design is distinct from realisation. It is essentially a process of knowledge construction about the artefact, about its realisation and, in a wider scope, about its expected life-cycle until disposal. The design process is in fact a model that, given the specific circumstances of the project (the business context, the nature of the artefact to be designed, the economic and social context, etc.), is instantiated for that specific project. The overall project methodology decides as to how to position the design phase (upfront, partially in parallel, with intermediate prototyping, etc.) in relation to the realisation phase of the project. Design as knowledge construction can be seen as a means to reduce uncertainty pertaining to the realisation and the further life-cycle of the artefact. Very often uncertainty is associated with risk but an over-designed artefact may reduce opportunities and flexibility in its use.
- *The design system*: is the set of resources (human, technical and knowledge resources) organised for executing the design process. Of course, the *designer* is a key element in the design system. A specific design situation is commissioned design, with a sponsor or a set of sponsors entering a relationship with one or more (professional) designers and whereby this or these designers are 'commissioned' to design a new artefact. Commissioned design in its simplest form exists for example between an architect and a client for designing a new house. Commissioned design situations, at least in professional situations, imply most often a higher level of explicitness of the information exchanged between both parties.

Themes of knowledge construction in the design space

Considering design as knowledge construction leads to the idea that knowledge is constructed in a certain space: the design space. The design process becomes a process of enriching the design space up to a situation whereby the level of detail and the level of consistency between the respective contents appears acceptable to the designer. This appreciation is not merely subjective since the designer may use external standards and norms or inputs from people so as to verify the content of the design space.

As said above, the domains of knowledge construction are: the artefact subdivided in artefact type with functional and embodiment properties, its realisation and its further life-cycle. In addition, criteria may be used to verify that the contents of these themes are correct and relevant. The main criteria consist of the project intent, the requirements, the constraints and norms and standards (figure 1).

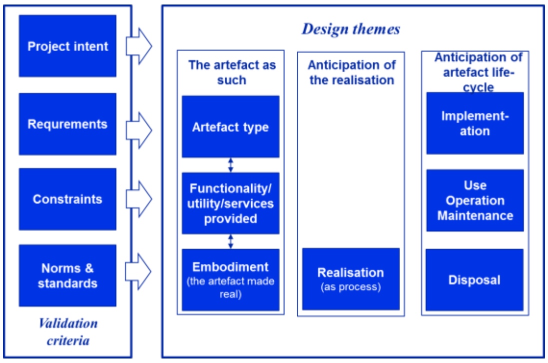

Figure 1: Themes in the design space

The right part consists of the themes that pertain to the artefact, the anticipation of its realisation and of its life-cycle (after realisation). The left part consist of all content that can be used for evaluating the contents of the right part.

The nominal content of the design space

The above definition of the themes in the design space is a 'nominal' definition. The content of the design space can vary depending on the needs of the project. For instance, in pure innovative design, it may not be possible to define requirements nor constraints and the entity 'artefact' may be limited to one set of constructs in the design space without further differentiation. In preliminary design, the focus may be on the artefact alone without attention for its realisation and its further life-cycle. In other cases, the entity 'artefact' may be further decomposed in more entities, each of them representing an alternative under consideration.

In fact, the themes of the design space in a specific project are those themes that have to be addressed explicitly. Obviously, these themes are in close relation with the objectives of design task to be performed.

Designer-centred analysis

The research project mentioned in the introduction is aiming at better understanding design, especially the general characteristics of design that are not proper to one specific discipline. In a lot of domains professionals are facing complex situations where different disciplines have to work together and a general theory of design may contribute to better communication and collaboration.

When deconstructing design, it appears that the individual designer is at the centre of the design process, even if he is interacting with other designers, users, sponsors and other stakeholders. It is the conviction of the authors that by better understanding what happens at the level of the single designer, it will be possible to build on this and to better understand interactions between individual and group behaviour.

Designer activities

When looking at the designer-in-action, he is involved in a series of activities that for the sake of simplicity can be grouped in three categories:

- The *cognitive* activities i.e. the process of information processing called 'high level', pertaining to memory, attention, etc. and more elementary processes such as perception and those involving motor skills.
- The *expression* activities whereby the designer expresses on some medium (paper, whiteboard, computer) part of the contents of the design space,
- The *interaction* activities whereby the designer interacts with the physical world (objects), with information sources (documents, data-bases, …) as well as with other people (designers, users, etc…)

This is an simplification as there are obviously (a) interactions such as between expression activities and communication and collaboration with people and (b) retroactions such the expression of design ideas that help in structuring these ideas in the mind of the designer.

It is important to notice that design process management (at design system, team of individual designer level) is not included in the designer's (core) design activities. It is considered to pertain to the management of the project, more specifically, to the management of the design phase.

1.2 Objective of this paper

The objective of this paper is:

- To try to explain design by using concepts from cognition science, in other words, to explain the less general (design) by something that is more general (cognition), using a model of cognitive activities applied to design,
- To analyse some of the implications of the cognitive activities on the design process.

2 STATE OF THE ART

Designing involves a continuous search for solutions and raises high demands on the thinking ability of a designer. Research on the essence of human thinking is the focus of cognitive psychology (Pahl & Beltz, 1996). The cognitive approach in design aims at developing theoretical models about the inner processes of an individual, so as to understand the cognitive processes underlying the performance of a task by specifying the different stages of information processing. Currently, there is no single integrating model that encompasses all cognitive processes. As stated by (Detienne 2002), mental processes involved in the design activity can be conceived as belonging to a complex cognitive task. Some cognitive functions are indicated in literature as accounting for the major cognitive processes developed during a design activity:

- Exploration and manipulation of knowledge and the construction of mental representations (Meunier, 2009), which was already indicated by (Visser, 2006) as being an essential element in design,
- In memory processes, two components appear to be relevant: the working memory (defined by Baddeley, 1996) that allows the manipulation of various forms of temporary representations and the semantic memory (according to Tulving, 1995) that belongs to the long-term memory(ies) that store(s) all our knowledge.
- The concept of metacognition introduced by Flavell (Flavell, 1979) provides an understanding of the importance of the own knowledge of our knowledge i.e. "to know that we know." Metacognition is knowledge of one's own cognitive activity and content or that of others, which allows the planning and control of it (Metcalfe & Dunlosky, 2009; Tarrigone 2011). Many studies have highlighted the impact of metacognitive processes on the capacities of acquiring new knowledge (Cauzinille-Marmeche & Weill-Barais, 1989; Nguyen-Xuan, 1990; Rozencwajg, 2003).

Experimental-based design research (Yoshikawa, 1983) or empirical-based design research (Gero et al., 1997) result in cognitive models of designing. Typical approaches are: direct observation of results of designing, survey of designer's perceptions and protocol studies of individual and collaborating designers during design. The most used technique is protocol analysis. It is an experimental method to analyse designers thinking. These studies consist of the following parts (Tomiyama et al., 1989): one or more designers are asked to solve a design problem and they are asked to say what they think while designing. What they say, what they do, what they draw and what they write are all recorded until design is completed. The recording and exploring is called protocol analysis (Ericsson et al., 1980). Several studies were reported in Yoshikawa's work (Yoshikawa, 1989; 1993; 1999).

For example, some authors propose a cognitive design model from problem-solving point of view (Tomiyama, 1995; Takeda et al., 1992). This model is based on the analysis of 494 protocols that were obtained during three design experiments to design a box handling mechanism for an automatic cigarette vending machine. Based on the analysis of data obtained, a unit design cycle is identified, which is composed of five sub-processes (Tomiyama, 1995): (1) awareness of the problems i.e. to pick up a problem and to compare the object under consideration with the specifications, (2) suggestion i.e. to suggest key concepts needed to solve the problem, (3) development i.e. to construct candidates for the problem from key concepts using various design knowledge, (4) evaluation i.e. to evaluate candidates in various ways, such as structural computation, simulation of behaviour, and cost evaluation), (5) conclusion i.e. to decide which candidate to adopt, while possibly modifying the description of object. In this model the designer's mental activity is modelled at two levels: one is design object level where the designer thinks about the design objects themselves; the other is the action level, where the designer thinks about how to proceed with the design, that is, to determine to do next.

Another significant protocol study is reported by Gero et al. (1997). Designers were asked to carry out a specified design task and the 'talk aloud' method was employed. While they are designing they are video-and audio-taped. The purpose is to study the time spent by a designer, either on postulating solutions or in reasoning about the function and behaviour of possible or postulated design. A typical distribution of the time spent between these two large classes of activities by a designer is obtained. It is worth to note that some researchers propose the cognitive design model from cybernetic point of view (Lhote et al., 1998). They consider all mental activity of design as a heuristic activity working in closed-loop. The model shows such iterative behaviour, combined with the generation of hypothetical solution and the projection of the solution in order to simulate all possible consequences and to compare them to the initial design specifications.

It can be noticed that protocol analysis as an inductive method for analysing design thinking has to be handled with care for different reasons: any expression of thoughts is modified by the 'channel' that is used (verbalisation, gestures, written expression), by the formalism, if any, and even by social factors: in most cases, people express only what is considered to be acceptable to the group they are in. On the other hand, thoughts happen at such a pace, in other words, the content of the short-term memory has such a degree of volatility so that only a part of what has been thought can be expressed.

(Visser, 1992) in studying the opportunistic character of design problem solving makes a similar distinction. She considers problem solving being modelled at two levels:

action execution (actual design problem-solving actions) and action management (action control) where decisions on the priorities of these problem-solving actions are taken. She finds, Further to the analysis of data obtained, she found that if several actions proposals were made, control would select the most "economical" action from cognitive effort point of view. She refers to the notion of 'cognitive cost' whereby the cognitive cost for an action is defined as 'the cost of accessing the required information and of its processing in order to achieve the goal of the action'. In later work, (Visser, 2006) stresses the nature of design as being not only problem solving bu also and most essentially, the construction of mental representations (cognitive artefacts).

As mentioned earlier, there are different approaches to cognition in design but there is no generic cognitive model that integrates the various cognitive functions. Several reasons can be advanced: the youth of the discipline and the fact that cognitive functions are dependent not only on the complexity of the activity but also its nature (Ashcraft 2006). Understanding mental activity as complex as design requires the ability to draw in the various theoretical models of cognitive processes that seem appropriate. One of the challenges is to integrate these different theoretical models in order to propose a model illustrating the various steps and thus cognitive processes underlying the design activity.

Although the C-K theory of (Hatchuel & Weil, 2002; 2010) does not refer to the cognitive approach in design, it aims at defining and describing design reasoning by differentiating two spaces: the C-space encompassing concepts and the K-space encompassing knowledge whereby a concept is a proposition without any logical status (true or untrue) and whereby knowledge is a proposition with a logical status. The theory defines four operators that (a) establish a disjunction between knowledge and a concept, (b) that expand the concept-space, (c) that expand knowledge-space and (d) that establish a conjunction between the concept and knowledge. The process that combines these operators is defined as the design process. Since it is neutral as to the type of artefact dealt with, it is claimed to be a general theory of design.

3 A MODEL FOR COGNITIVE TASKS

Before addressing cognitive activities in design, a model for cognitive tasks is developed. Thereafter, design shall be shown as being a particular instance of a cognitive task.

3.1 Definition

A cognitive task is defined as goal-oriented set of cognitive activities. In other words, it is goal-oriented thinking for a task that has been set by a person to himself or that has been allocated to the person by another one. Examples of cognitive tasks are: problem solving, planning and design.

3.2 Rationale for the construction of the model

The model is build upon key concepts:

- *Data, information, knowledge and representation*: it is essential to understand the differences between the concepts of data, information, knowledge, and representation. This data can be verbal, tactile, visual, etc. Information is built on data (Dretske, 1981): it is a significant association (i.e. making sense of) of data that is specific. There is a causal relationship between information and knowledge. The information is stored and organised in the long-term memory in the form of knowledge. Inferences are made out of knowledge. When manipulating this knowledge we do it through mental representations i.e. mental contents corresponding to transient information being processed in the working memory. This mental content is permanently stored in the long-term memory in the form of knowledge consisting of stable representations. Thus, "logical procedures and calculation processes are characterised treatments that modify the representations and allow the construction of knowledge." (Launay, 2004).
- *Cognition* is the set of content (knowledge) and content-processing capabilities (know-how or 'routines') that an individual accumulates over his lifetime through perception, interaction with the world, including himself, and internal processing.

3.3 Assumptions

- The mind learns through information acquisition: perception, action and retro-action and communication with others.
- The mind restructures its cognitive content and routines (processing capabilities). This re-organisation can lead to the creation of structures such as classes of objects or routines or to the decomposition into components that can be re-used elsewhere, similar to the decomposition of objects into components.
- The mind constructs cognition on cognition: meta-cognition, for instance, the mind may develop a discourse upon a series of events experienced by the individual.

3.4 Model components

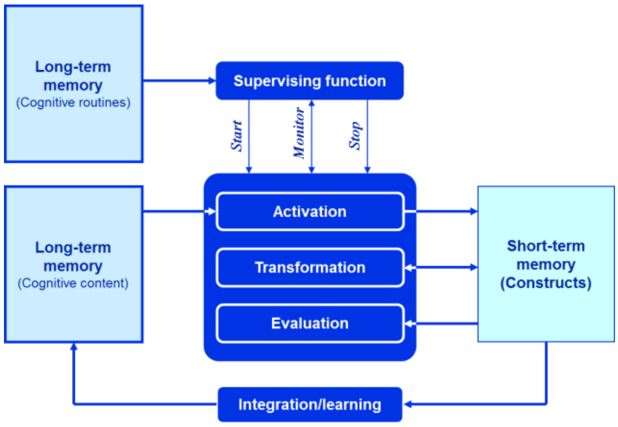

Figure 2: A model for cognitive activities in a cognitive task

The model consists of the following building blocks:

The long-term memory

The long-term memory contains:

- *Cognitive content (knowledge):* this memory consists of the perceptive memory with contents pertaining to the perception through the five senses, the semantic memory with the general knowledge of the world and the episodic memory containing events associated to contexts and autobiographical events (Eustache et al. 2008; Tulving, 1995). Episodic and semantic memories are considered explicit memory that is to say that the subject is aware of its contents (the role of meta-cognition) (Tulving, 1995). Knowledge is stored in the semantic memory. It can be static, such as mental images or schemes of situations, or temporally organised in episodes. The cognitive content can be perceptual or constructed i.e. cognition built on the perceptual cognition. Such cognition built on other cognition is not necessarily verbal (think of people seeing structures in objects or structures in music). The access paths to cognition in the long-term memory can be quite diverse: by concept (label, name) of an object, a person, etc., by analogy, by affect that the individual has experienced in a given situation, by cognitive structure (a model that has been interiorised) and by external triggers such as the manipulation of an object (see 'la madeleine de Proust').
- *Routines:* interiorised processes that have been appropriated through learning or that have emerged as action patterns through exercise and repeated application.

This memory pertains to both verbal, perceptual and motor skills (Anderson, 1993) and (Jacoby, 1983).

The short-term memory

The short-term memory is the working memory of an individual and contains constructs i.e. activated content that comes from the long-term memory (Baddeley, 1990; 1996). Activating the working memory is dependent on the needs of the activity to be performed. The constructs in the short-term memory are volatile and if they are not refreshed they simply disappear. Manipulation of knowledge is done at the level of the working memory (Richard, 2004).

Cognitive processes

Cognitive processes are abstractions for the set of routines that are proper to a given person and that pertain to the categories listed below. Conversely, a routine is considered as an instance of a cognitive process. The cognitive activities then correspond to the routines as they are executed in real time. The cognitive processes establish the logical relation between the content of the long-term memory and the short-memory. For each category of routines, there is at least one routine that a person can apply namely trial-and-error.

The basic processes in cognitive task are:

- The *activation* of cognition in the long-term memory and projection in the short-term memory as one or more cognitive constructs.
- The *transformation* of the constructs in the short-term memory by modification of one or more constructs, by assembly, by restructuring etc. Examples of transformation are: top-down decomposition, bottom-up assembly, and simplification by reducing the number of elements.
- The *evaluation* of the content of the short-term memory. Evaluation can be done at the level of one construct, at the level of a set of constructs or between sets of constructs such the comparison of alternatives.

As said, processes refer to sets of routines in the sense that they encompass all the range of routines an individual actually is capable of for executing a particular process. For instance, the evaluation activity may be done intuitively according to some implicit criterion such as 'like-dislike'. On the other hand, the designer may invoke an appropriated method to evaluate exhaustively the adequacy of the properties of an artefact to the requirements, by quoting it or by measuring it according to a specific method.

There are three additional processes:

- The *supervisory process* that controls explicitly the execution of the processes and their instances, the routines. Explicit means that the person is aware of the process. The supervisory process is in charge of loading routines i.e. making them available for execution, starts them, interrupts them, resumes them and finally terminates them (or inhibits them). The supervisory process determines also the respective priority of the routines. It is assumed that not all routines are explicitly controlled. Further to the formation of habits, routines can become automatic and they can trigger the execution of other routines so that chains of routines can be formed. In such a case, the individual is not aware of the transition between routines.

- *Exception handling* (problem solving): when a problem arises, the supervisor may start another routine for instance, when a decision has to be made about alternatives, when there is lack of convergence or when contradictions emerge. If changing routines does not solve the problem, then a process of exception handling (problem solving) may be started whereby the whole working space and the routines used so far become the subject of activation, transformation and evaluation. This may lead to changes in the constructs, to changes in the routines used, to changes in the type of artefact being considered (for instance, a designer thinking about a car can invoke knowledge pertaining to bicycles), or to changes in the sequence of themes dealt with in the working space (for instance, a designer having started with the requirements may tackle the problem starting with the artefact).
- The *consolidation process* (part of) the content of the short-term memory is consolidated and integrated in the long-term memory. This process is mostly implicit.

3.5 Evolution of the content of the working space

During the design process, the content of the working space evolves by enrichment (activation of cognition) and transformation and becomes progressively more consistent. Hence, the design process corresponds to a series of states of the working space:

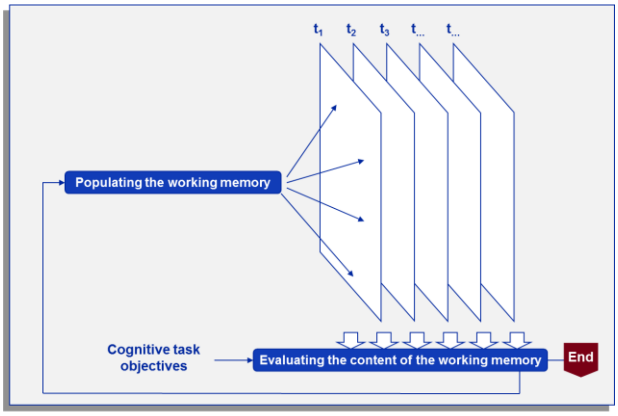

Figure 3: Evolution of the states of the working memory

In the schema, a plane represents the design space at a given moment t_i: the working space changes because the content is enriched (for the respective themes) as it is transformed by adding, suppressing, modifying, merging or decomposing constructs and because the contents are evaluated and made consistent within and across themes. In parallel, as a meta-process, the overall working space is assessed so as to evaluate whether it is is sufficiently detailed and consistent given the objectives of the specific task.

3.6 Assessment

The proposed model represented in Figure 2: A cognitive process model for a cognitive task, is an input-output model (from long-term memory to short-term memory) through the processes of activation, transformation and evaluation. The model involves feedback, which is an alternative term for learning:

- On the content of the working space: via the evaluation process, which leads to additional activation and or transformation
- On the content of the long-term memory: due to the consolidation process
- On the choice and the content of the routines: through the exception handling process.

4 DESIGN AS A COGNITIVE TASK

4.1 The specificity of design as a cognitive task

Design can be considered as a cognitive task. Indeed, when considering the designer's activities, design is essentially mental even when interacting with the external world (people, objects and information sources). Following elements are typical for design:

- *The target content of the working space*: when a designer has a new design task, the objectives are set by the sponsor or by himself, and the term 'design' invokes a series of themes to be developed. This can be the nominal list of themes (see §1.3.2) or depending on his experience and the specific context he is in, the themes may be organised differently.
- *The content of the long-term memory that is activated*: during design, two classes of situations and episodes may be activated by priority: (a) the situations and episodes pertaining to artefacts that are deemed interesting and the interaction with these artefacts along their life-cycle and (b) the situations and episodes pertaining to projects done in the past, including design but also activities such as realisation, maintenance, etc..
- *The routines that the designer mobilises*: the designer will try to use for the design task at hand the routines that worked in the past and when problems arise, he will tend to apply the exception handling routines he successfully used in the past.

It should be noticed that reframing the design task during the exception handling process may lead the designer to activate other cognitive content and other routines that are not specific to design. In fact, it is up to the designer to activate all his knowledge and experience, as needed. This furthers creativity and innovation. Of course, he will also get additional knowledge during the interaction with people and objects.

4.2 Design space and working memory

The concept of design space as used in this paper relates to the short-term memory as follows: it is an abstraction of the constructs in the short-term memory in the sense that only the constructs deemed relevant for design are taken into account, the remaining constructs being considered as 'noise'. The notion of 'noise' is relative: in fact the designer may deal with two design tasks in parallel. What is noise for on task may be essential for the other. Moreover, such parallel processing may be a source of inspiration by activating other cognitive content.

4.3 Design activities: beginning and end

In commissioned design i.e. when designer is put in charge of a design by a sponsor or client, the design starts when the commission is officially given to the designer. From a cognitive point of view, the design may start at that moment or may have started much earlier if the designer was already interested in the subject.
Similarly, the project may foresee a given time-budget for the design task whilst the designer may be 'obsessed' with his design, night and day. And when the project is terminated, he may go on and find still better characteristics for the artefact that has been designed.
From a cognitive point of view, design ends when the designer considers the themes in the design space sufficiently complete and consistent. From a project point of view, design ends with the acceptance by the sponsor and more specifically, when he considers that sufficient knowledge has been built up so as to reduce the uncertainty (risk) associated with the later phases of the project.

5 AN EXAMPLE

5.1 Introduction to the example

The example below pertains to a case-study in a specific workshop for students of a master degree. Although the case is not aimed at identifying cognitive activities, it seems useable, at least as an illustration, and because it provides an opportunity to (try to) identify the cognitive activities that were deployed.

The case is about designing a pen of moderate cost that should boost the revenue of a medium-sized company producing and distributing office supplies. At the start, the target artefact seems defined (it is a pen) but there are different types of pens (fountain pens, ballpoints, rollers, pencils), re-useable or not, with different type of cartridges, with different materials and so on. The number of degrees of freedom is considerable and the uncertainty high.

The case is organised in two sub-tasks: requirements definition and artefact design (properties, structure and embodiment).

5.2 Design theme: Requirements

The first sub-task consists of understanding the written input material and identifying the 'stakeholder' (the sponsor, the sales responsible, the distributors, the students and the parents), the project intent as formulated by the sponsor, as well as the needs of the different stakeholders.

<u>Design activities performed</u>: interaction for information appropriation, *activating cognition* from previously known situations so as to imagine the needs for the different stakeholders, *transforming the contents* of the design space for organising the list of needs, *evaluation* of the completeness of that part of the design space (Are all stakeholders mentioned? Do they have specific needs?), and finally, expression of the needs for instance, in a list or in a table with stakeholders and needs. In the beginning, these needs may be contradictory, which creates a challenge to the design team.

Unless the designers have had previous experience in defining needs or unless they contact directly the stakeholders (simulated by the person in charge of the workshop), the list of needs will depend essentially on the cognitive content the designers are able to activate.

The second part of this task is to extract from the above list of needs, the required properties and constraints that are applicable to the pen that has to be designed. Once again, it requires the designers to invoke their cognition (a) of situations where they have used a pen for whatever reason (writing, showing their social position with an expensive pen, etc..) or where they have seen other people using a pen (think of reloading a new cartridge, of accidents in using an ink bottle or breaking a pen, etc…), (b) of previous design situations where they were dealing with requirements.

<u>Design activities performed</u>: *activation of cognition* about pens and possibly of other pens, *transforming the contents* of the design space (theme: requirements), *evaluation* and expression the list of requirements).

Unless the designers follow a prescriptive method or a well-established routine, the design activities occur at random with transitions between activation, transformation and evaluation, depending on their associative thinking.

5.3 Design theme: Artefact

The second sub-task involves (a) the definition of the artefact (a single pen, a set of pens, a package with a pen, cartridges and eraser) that is specific of certain commercial circumstances (Christmas gift), (b) the identification of one or more alternatives, (c) the evaluation of the alternatives and (d) the selected versions of the pen that are proposed and a simple bill of materials so as to list the required materials.

Designer activities performed: *activating cognition* pertaining to pens (types of pens, properties relating to these types, situations of utilisation, users, events (f.e. failure) with impact, *transforming* the content of the theme artefact, according to different transformation routines such as starting from a given pen and progressively transforming it after *evaluation* on the basis of the requirements, or comparing two or more alternatives, or, on the basis of two or more known pens, defining a new pen having a series of components and properties.

Some designers started with one type of pen (they know) and they let vary form and components so as to comply with the requirements. Others decided rather soon in dealing with two or even more types of pens (fountain pen and ball pen). A few designers activated also cognition that does not immediately pertain to pens, by proposing a plastic package in the form of Christmas tree or a pen form like a rocket or by varying the engraving of the pen: strip figures for junior students and mathematical formulae for high school students.

In practice, the designers iterated on the themes of the design space that are in scope but they also iterated between themes i.e. between requirements and artefact.

The elements of the different themes in the design space have a life-time in the short-term memory and should be refreshed so as to be re-integrated in the long-term memory. In some situations, it was observed that the students forgot in the final presentation part of the content they had dealt with during the actual design.

6 DISCUSSION

6.1 Findings

- *Another perspective on design*: the design process is considered as knowledge construction in the design space. This knowledge is needed so as to reduce uncertainty (risk) associated with the further phases in the realisation, use and disposal of the artefact. The focus is on achieving the adequate level of detail and of consistency and not so much on the correct execution of a series of steps. In a project, between two successive moments for synchronisation with other people (milestones), the designer may appear to behave 'chaotically' i.e. moving very swiftly across the design space from one construct or theme to another due to associative thinking (one idea triggering the other, such as a new requirement leading to consider other artefact-types).
- *Design as a specific cognitive activity*: design is a specific cognitive task, essentially by the definition and the progressive enrichment of the design-specific themes in design space. The design can use design-specific content and design-specific routines but ultimately, the designer can mobilise his full knowledge and experience, even when this knowledge and experience is apparently not related to the design at hand. The proposed model shows that the specificity of design depends on the themes that have to be dealt with in the design space. Moreover, there is no restriction on the types of constructs that can be activated in the working memory: concepts but also images, sounds, smells, etc.
- *Design is a learning process*: the consolidation process integrates the contents of the design space in the long-term memory as an extension of the designer's knowledge and experience
- *The explaining power of the model*: the model provides a global explanation of the cognitive activities at the level of the interactions between the long-term and short-term memory. The model is not predictive as the cognitive content and the routines are proper to each individual designer. The role of design methods and techniques, such as creativity techniques, can now be better understood; they have to be appropriated (acquired) by the designer, with possible modifications, in order to become routines the designer may invoke when needed. Similarly reference models and architectures that propose a structured set of subjects to be dealt with may help to define in more detail the themes the designer will have to enrich and to complete.
- *The use of the model*: the model can help a designer in developing meta-cognition about design. Before, during and after a given design process, he may use the model so as to assess the cognitive content he will use or is using or has used. The same can be said for the routines. He may become aware that at a given moment in time, there is a whole of cognitive resources he has not yet mobilised.
- *The relation with the C-K theory* (Hatchuel, 2002,2008): there seems to be some symmetry between the proposed model (with the long-term memory and the working memory) and the C-K theory (with the concepts space and the knowledge space. However, the proposed model has emerged on the basis of cognitive science and the C-K theory seems to aim for the logic of designing. It would be worthwhile to investigate how the concepts in the C-K theory relate to the notion of cognition and meta-cognition.
- *The relation with the cognitive artefacts (Visser, 2006):* the proposed model is in line with the statement that design deals with mental representations but is more specific and identifies the nominal list of design themes wherefore constructs are activated and assembled. It shows also the particularities of design as a specific cognitive task.

6.2 Conclusions

The authors believe that this model is first-order model in the sense that further research will lead to a more complex model with additional elements or a refinement of those currently present. Nevertheless, it already contributes to a better understanding of design as a quite general process i.e. that goes beyond specific disciplines. More work appears to be necessary in a series of areas, through the integration of existing contributions or by further research: in the structure of design knowledge and experience, in the process dynamics, specifically, in the transitions between the execution of the core processes and the exception handling process and, obviously, in the relation between the cognitive activities and the interaction and expression processes.

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