Contribution to a general theory of design

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THESE

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CONTRIBUTION A UNE THEORIE GENERALE DE LA CONCEPTION

Résumé

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INTRODUCTION

La conception va de pair avec l'action humaine visant à transformer, de manière volontariste son environnement. Son importance croît une tendance générale à l'innovation dans un monde globalisé. La complexité des projets augmente : de plus en plus de facteurs sont à prendre en considération nécessitant des démarches et des équipes multidisciplinaires. Or la plupart des méthodologies de conception et des théories qui les fondent sont propres à des domaines particuliers comme l'architecture et l'ingénierie et ne rencontrent pas les besoins du travail multidisciplinaire.

Comme l'action de conception est une activité principalement humaine, il est naturel de poser la question dans quelle mesure il existe des éléments communs à tous, sinon un grand nombre de domaines et contextes de conception.

Cette question se pose à trois niveaux : celui de la recherche en conception, où une théorie générale devrait permettre de formuler de façon compacte et économique les acquis de la recherche, celui de la pratique de conception, pour la facilitation du travail d'équipes de formation et de culture différentes enfin, pour aider des futurs concepteurs à fonctionner dans une monde qui dépasse le cadre de leur formation initiale.

L'objectif de la thèse a été formulé en conséquence, contribuer à une théorie générale de la conception qui soit explicative. La théorie générale recherchée se doit d'être (a) *explicative* c.à.d. qu'elle doit expliquer des phénomènes spécifiques par des concepts et considérations plus généraux, (b) *générale* c.à.d. indépendante d'un domaine ou d'un mode de conception particuliers et (c) *globale* (« comprehensive», en anglais) c.à.d. elle doit englober l'ensemble des variables essentielles de la conception sans se limiter uniquement au processus de conception.

ETAT DE LA QUESTION

En vue d'établir l'état de la question, la multiplicité des sources concernant la conception a conduit à explorer surtout les sources qui parlaient explicitement de théorie de la conception. D'autres sources en traitent implicitement, par exemple, dans les domaines de la résolution de problèmes et des sciences cognitives ; elles ont aussi fait l'objet d'un examen approfondi, dans la mesure où il existait un lien fort avec la conception.

L'évaluation des sources retenues a été faite sur base des trois exigences formulées pour la théorie (voir plus haut) et la nécessité de traiter, selon Dorst (2007) des thèmes suivants : le contexte, l'objet, le processus et l'acteur de la conception. Il en ressort qu'aucune des théories existantes ne couvre les quatre thèmes, que la plupart sont confinées ou fortement associées aux domaines de l'ingénierie et de l'architecture et surtout aux objets techniques, et qu'en fin de compte aucune ne rencontre complètement les exigences mises en avant pour une théorie générale de la conception.

CONTRIBUTION

La structure de la théorie est constituée d'un cadre conceptuel à six thèmes interdépendants : le projet, l'artefact, l'espace de conception, le processus de conception, l'organisation de conception et les activités du concepteur. Il est fondé sur une logique simple : le projet génère l'artefact; la conception est une construction de connaissances à propos de l'artefact, dans l'espace de conception; la conception est mise en uvre par l'organisation de conception et parmi les ressources qui composent cette organisation, c'est le concepteur individuel qui, en définitive, réalise les activités de conception, en interaction avec les autres personnes de l'organisation.

Le **projet** forme le contexte pour l'activité de conception. Il y a au départ d'un projet, incertitude de par le grand nombre de degrés de liberté quant à l'artefact à réaliser et incertitude quant aux étapes ultérieures de la vie de l'artefact. L'incertitude peut s'interpréter à la fois comme risque ou comme flexibilité et facteur d'opportunité. Lorsque cette incertitude n'est pas acceptable, au point d'entamer directement la réalisation de l'artefact, il y a lieu de la réduire par une construction de connaissances. De cette considération dérive la fonction de la conception au sein d'un projet : c'est une construction de connaissances à propos du futur artefact afin de réduire l'incertitude.
La méthodologie de projet définit la façon suivant laquelle on va conduire l'activité de conception, en une ou plusieurs phases, chacune avec des objectifs spécifiques, et la position de l'activité de conception par rapport à la réalisation, en séquence, en parallélisme partiel ou en parallélisme total.

Un **artefact** est un objet inventé et réalisé par une intervention humaine. Un accent particulier a été mis sur la nature subjective et contingente de l'interaction d'un agent avec un artefact : la fonction et l'ergonomie perçues d'un artefact, dépendent à la fois de l'agent, du type d'interaction avec l'artefact et du contexte. Par voie de conséquence, l'artefact conçu par un concepteur dans un certain but n'est pas nécessairement perçu en tant que tel par un autre agent.
Les classes principales de propriétés d'un artefact sont le type, la fonction, l'ergonomie au sens de la possibilité, pour un agent donné, de perception et d'interaction avec l'objet, et sa concrétisation (en anglais, «embodiment »). La notion de fonction se décline en trois dimensions : la fonction identitaire (le r le et l'utilité de l'artefact pour l'identité de l'agent), la fonction relationnelle (le r le et l'utilité de l'artefact pour l'agent dans ses relations avec d'autres) et la fonction technique (le r le et l'utilité de l'artefact pour l'agent dans son action sur son environnement physique). Une voiture de luxe illustre parfaitement ces trois dimensions : la fonction technique (le transport), la fonction relationnelle (le prestige) et la fonction identitaire (le plaisir de posséder et de conduire une voiture confortable et performante).

L'**espace de conception** est l'espace virtuel où agit le processus de conception. C'est l'endroit où sont explicitées et où sont gardées les connaissances développées pendant la conception. En théorie, on ne peut parler que du contenu 'nominal' de l'espace de conception. En effet, suivant les situations, le concepteur peut modifier le contenu-cible de l'espace de conception, en éliminant certains aspects ou au contraire, en y ajoutant d'autres.
Le contenu nominal comprend (a) les critères de conception, permettant de valider l'artefact conçu (l'intention de projet, les exigences relatives à l'artefact, les contraintes et les standards applicables), (b) la description de l'artefact (le type, la fonction, l'ergonomie, la concrétisation), et (c) l'anticipation des phases ultérieures dans le cycle de vie de l'artefact depuis sa réalisation jusqu'à sa destruction ou son recyclage.

Le **processus de conception** est une abstraction des activités de conception et comprend les sous-processus : appropriation des entrées (des informations provenant des phases précédentes du projet ou provenant de recherche d'information), construction de connaissances dans l'espace de conception et génération des sorties, les résultats intermédiaires ou finals de la conception.

L'**organisation de conception** est l'ensemble des ressources affectées à la conception. Le processus de la conception est instancié une première fois au travers de la ou des phases de

conception pour un projet donné, et une deuxième fois par décomposition en tâches de conception et leur allocation aux ressources.
La thèse s'est limitée au thème de l'instanciation. L'étude des différentes formes de l'organisation de conception, de la dynamique des équipes de conception et de leur impact possible sur la conception, dépasse largement le périmètre d'un travail de thèse où l'accent a été mis plus la compréhension globale plutôt que sur le détail de chaque thème.

Le concepteur, au sein de l'organisation de conception, déploie **trois types d'activités** : les activités cognitives, les activités d'expression de contenu cognitif et les activités d'interaction, avec d'autres personnes (communication et collaboration), avec des artefacts (comme source d'inspiration) et avec des outils de conception.
La thèse s'est focalisée sur les activités cognitives. Un modèle de t che cognitive est proposé, articulé autour des concepts de mémoire longue durée, de mémoire courte durée (mémoire de travail), de trois processus cognitifs de base agissant sur la mémoire courte durée (activation, transformation et évaluation) et de contenus cognitifs, statiques (savoir) et dynamique (expérience).
Le modèle général, devient spécifique de par le contenu-cible associé à la tâche de conception et de par les contenus spécifiques que le concepteur y introduit.

ETUDE DE CAS

Une étude des cas a permis de mettre en évidence les différents concepts de la théorie. Sa complexité paraît suffisante par rapport au but poursuivi, tout en éliminant les éléments qui dans les projets s'ajoutent et interfèrent avec les activités de conception pure.

CONCLUSIONS

Le cadre de référence proposé décompose la notion de conception en ses éléments constitutifs et en décrit les aspects importants. Il est limité par le niveau de développement actuel des sciences cognitives notamment au niveau des liens entre cognition et émotion. La théorie contribue à expliquer notamment que dans la pratique, le comportement du concepteur peut paraître chaotique alors qu'en fait, il est régi par les processus et les contenus cognitifs (le savoir et l'expérience) de ce concepteur, pour la t che de conception donnée.

Par rapport aux exigences formulées vis-à-vis d'une théorie générale de la conception, le cadre de référence apparaît comme un proposition valable en termes de pouvoir explicatif (de l'intention de projet jusqu'aux activités cognitives du concepteur), de généralité (prise en compte de la diversité des artefacts et la variété de situations conceptions) et de globalité (la conception est située dans le contexte du projet, elle est une construction de connaissances et elle peut être déclinée par de organisations de conception fort différentes, allant du concepteur isolé à des organisations de conception complexes).
Les limites de cette contribution sont doubles : d'abord, au niveau de l'organisation de la conception et d'autre part, à celui des interactions du concepteur avec le monde extérieur (personnes, artefacts, outils) et de ses activités d'expression de contenu cognitif, rétroagissent sur les activités cognitives. Les sciences cognitives peuvent sans doute y contribuer.

Au-delà du perfectionnement de la théorie en soi, celle-ci, au travers du cadre conceptuel, permet de situer toute une série de domaines de recherche qui peuvent l'enrichir, depuis la théorie des artefacts à la psychologie du concepteur, en passant par les stratégies de conception, la gestion de connaissances de conception, les organisations de conception et la dynamique de groupes de conception.

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CONTRIBUTION TO A GENERAL THEORY OF DESIGN

Summary

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INTRODUCTION

Design is closely associated with the human endeavour to voluntarily transforming the environment. Nowadays, its importance is growing with the stronger focus on innovation in a globalised world. The complexity of projects is increasing: more and more factors are to be taken into account so as to require multidisciplinary approaches and teams. However, most design methodologies and the underlying theories are proper to specific domains such as architecture and engineering and do not cope with the needs of multi-disciplinary work.

Since the activity of design is in essence a human activity, it is natural to raise the question whether there are common elements if not to all design domains and contexts, at least to most of them.

This question can be considered at three levels: design research where a general theory may be able to formulate in a compact and economical way results of research, design practice where the communication and collaboration between teams with different background and culture may be facilitated and finally, design education where there is a need to open the minds of future designers for allowing them to operate in a world that lies beyond their initial specialism.

The objective of this thesis has been defined accordingly: to contribute to a general theory of design. The theory looked for has to be (a) *explanatory* i.e. it has to explain specific phenomena using more general concepts and considerations, (b) *general* i.e. independent from a specific domain or design modes and (c) *comprehensive* i.e. it has to address all the key variables of design and not be restricted, for example, to the design process.

STATUS QUAESTIONIS

In order to establish the Status Quaestionis, the multiplicity of sources led to explore mainly the sources dealing explicitly with design theory. Other sources address the subject in an implicit way, for example, in the domain of problem solving and cognitive science. These sources were considered too in as much there was a strong relation with design.

The evaluation to the sources has been based on the three requirements put forward for the theory (see above) and on the need to deal, according to Dorst (2007), with the following themes: the context, the object, the process and the agent of design. It appears that each of the existing theories examined does not address all of themes, that most of them are limited to or closely associated with engineering and architecture and principally with technical objects and finally, that none of them fits completely with the requirements defined for a general theory of design.

CONTRIBUTION

The structure of the theory is formed by a conceptual framework with six interdependent themes: the project, the artefact, the design space, the design process, the design organisation and the activities of the designer. This framework is based on a simple rationale: the projects generates the artefact; design is a process of knowledge construction about the artefact, in the design space; design is put into practice through the resources of the design organisation; it is the designer who actually carries out the design activities, in interaction with the other members of the design organisation.

The **project** constitutes the context for design. There is, at the start of a project, uncertainty given the high number of degrees of freedom pertaining to the artefact and uncertainty as to the later steps of the life-time of the artefact. Uncertainty can be interpreted as risk as well as flexibility or opportunity factor. If the level if uncertainty is not acceptable, it is reduced by the construction of knowledge. This consideration leads to the identification of the role of design in a project: it is knowledge construction about the future artefact in order to reduce uncertainty.
The project methodology defines the way how the activity of design will be realised, in one of different phases, each of them with specific objectives; it defines as well the position of design in relation to realisation i.e. in sequence, in partial or in full parallelism.

An **artefact** is an object invented and realised by human intervention. A particular focus has been put on the subjective and contingent nature of the interaction between an agent and an artefact: the perceived function and ergonomics of an artefact depend on the agent, the type of interaction and the context. As a consequence, an artefact as conceived by a designer will not necessarily be perceived as such by another agent.
The main property classes of an artefact are the type, the function, the ergonomics considered as the possibility, for a given agent, to perceive and interact with the artefact, and finally, the embodiment. The function is considered to have three dimensions: identity-related (the role and utility of the artefact for the identity of the agent), relational (the role and utility of the artefact for action in the physical environment). A premium car perfectly illustrates the three dimensions: the technical function (transportation), the relational function (prestige among others) and the identity-related function (the pleasure to own and drive a high-performance and comfortable car).

The design process acts on the **design space**. Design knowledge is constructed in this virtual space. In theory, one can only talk about the 'nominal' content of the design space. Indeed, depending on the situation, the designer will add to the target content of the design space or delete other elements.
The nominal content consists of (a) the design criteria that are used to validate the conceived artefact (project intent, requirements, constraints and applicable standards), (b) the description of the artefact (type, function, ergonomics and embodiment) and (c) the anticipation of the later phases in the life-cycle of the artefact from realisation to the ultimate destruction.

The **design process** is an abstract model of the design activities and consists of following sub-processes: appropriation of inputs (coming from previous project phases or obtained by (re)search), knowledge construction in the design space and generation of outputs (intermediate or final design results).

The **design organisation** is the set of resources allocated to design. The design process is instantiated a first time through the definition of the single or multiple design phase(s) in the project and a second time by decomposition of the design phases into design tasks and their allocation to the resources.
The thesis has been limited to the instantiation aspect. The study of the different forms of design organisations as well as of the dynamic behaviour of design teams and their impact on design is largely beyond the scope of this thesis where the focus has been put on overall comprehension and not on the details of each theme.

A designer, within a design organisation, deploys three types of **design activities**: cognitive activities, expression activities and interaction activities with other people (communication and collaboration), with artefacts (as a source of inspiration) and with design tools.
The thesis has been focused on the cognitive activities. A model of cognitive task is being proposed, articulated on the concepts of long-term memory, short-term memory (working memory), three cognitive processes (activation, transformation and evaluation) and cognitive content (static i.e. knowledge and dynamic i.e. know-how).
This general model becomes specific through the target content of the working memory associated with a given design task and through the specific content generated by the designer.

CASE STUDY

A case study allowed illustrating the different concepts of the theory. Its complexity appeared adequate for this purpose while elements which in project add on and interfere with the pure design activities have been deleted.

CONCLUSION

The conceptual framework decomposes the notion of design in its constitutive elements and describes the most important aspects. It has limitations given the current state of development of cognitive science, specifically where the relation between cognition and emotion is concerned. The theory helps to explain for instance, how in practice, the behaviour of a designer may appear chaotic while it is governed by the designer’s cognitive processes (know-how) and content (knowledge) applicable to a given task.

As to the requirements put forward for the theory, this conceptual framework appears to be a valid proposition in terms of explanation power (from project intent to the cognitive activities of the designer), of general character (the diversity of artefacts and of design situations being taken into account) and of comprehensiveness (design occurs in the context of a project, it is knowledge construction and it can be deployed by quite diverse design organisations, from a single designer to a complex design organisations).
The limits of the contribution are twofold: first, at the level of the design organisation and second, at the level of the interactions of the designer with the external world (people, artefact and tools) and the expression activities of cognitive content, which retroact on the cognitive activities. Cognitive science may well contribute to it.

Beyond its improvement as such, the theory, through the conceptual framework, allows situating a series of research domains, from artefact theory to the designer’s psychology, via design strategies, design knowledge management and design team dynamics.

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Contribution to a General Theory of Design

Ph.D. Thesis by J. HUYSENTRUYT

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1 OVERALL INTRODUCTION

This chapter introduces the origins and the motivations of this research in design theory, assesses the importance of design and the needs for a general design theory, reviews historical developments of design theories and defines the research objectives and the methodology followed.

1.1 Origins of and motivations for research

The origins of this research on design theory, are quite old and date from the late sixties, at least where engineering design is concerned. This interest evolved from documenting in some automatic way the design of information systems and later, of any type of system, to supporting the design of systems with a tool, still later, to designing such a tool and finally, to defining of a language able to express such a design. In the end, it stabilised in the form of 'design theory' in analogy with the then popular mainstream ideas of problem solving (Simon, 1972) and systems theory (Von Bertalanffy, 1968) and (Lemoigne, 1977).

The interest for design theory was also associated with professional activities: applying project and system development methodologies, teaching them and contributing to their development and application. One recurring problem was the fact that many methods and methodologies in that period seemed to be based on implicit theories and hypotheses that were weakly founded by some kind of theory. This often led, during training courses on methods, to embarrassing questions by students who were not only interested in the 'How?' but also in the 'Why?' of a methodology. When the theoretical foundation was lacking, the inevitable answer was that the methodology had been derived from the practical experience of 'experts'.
Another trigger was the need for justifying design decisions and process rationale towards colleagues, project managers and clients.

Finally, it has always been curious to find out that neither in the author's engineering education and in the education of other students from other universities, years later, so little importance was given to design theory and design methodology in comparison with the attention paid to technology and mathematical models. It is strange indeed since design might be considered as one of the core activities in engineering.

1.2 Design and design theory

1.2.1 The growing importance of design

<u>The importance of design</u>

"We live in a designed world" (Buchanan, 2010). Indeed when looking around, one sees all kind of initiatives and realisations by human beings in transforming intentionally their environment for subsistence, for protection against the threats of nature, for transportation, for communication and collaboration, for exploration, …. With the ever increasing production and consumption of material goods,

human beings have arrived at the point where the transformation of their environment affects the whole planet, for good and for bad.
Design cannot remain focused alone on the artefact that is to be realised but it has to anticipate more and more the effects of such an artefact, of its existence, its use and ultimately, its disposal. The declaration at the Earth Summit in Rio de Janeiro (1992) about the notion of precautionary principle (Principle#15) goes in the same direction.

For individual firms, design is closely related to innovation. In a competitive environment, firms have to innovate and therefore, to design new products, new services, new processes, new tools, new organisations and they have to do more rapidly and more efficiently. “Design is the heart and soul of an enterprise (Peters, 2005).

Although the exact figure of the cost committed during design (Barton, 2001) may be discussed, there seems to be a large consensus that design determines a large part of it and hence, considerable attention has to be paid to this activity.

1.2.2 The need for design theory

In the field of design research, terms that are frequently used are: design science, design methodology, design theory, scientific design and science of design (Beitz, 1994). For (Dorst, 2007) “the aim of design research is to observe, to describe, to explain and to prescribe (design)”. He goes further by stating that key elements to be dealt with in the research are: the object of design, the actor, the context and the process. Until recent years there was an overwhelming focus on the process.

As design science progresses, it is natural to try, from time to time, to integrate the different contributions or at least to provide for frameworks that allow situating the contributions of the different research domains (or from the different schools). This fosters comparison, critique and cross-fertilisation.
A theory is meant to be a rationalised set of generic concepts that at least explains what design is and how design comes into being. In other words, as compared to the wealth of research results about the most diverse design situations, a theory proposes an abstract, economic structure with a limited number of concepts and relations between these concepts. The design research done since tens of years (Bayazit-2004) and (Andreasen-2011) has resulted in a limited number of theories that aim at explaining design in a comprehensive way i.e. by addressing these key elements cited by Dorst.

There appears to be a need for a general design theory for reasons of:

- *Design research*: there is a periodic need to consolidate and to structure the knowledge that is being progressively developed. Moreover, if one wants to stress the use of experimental research methods as suggested by (Dorst, 2007), a theory of design can provide a consistent set of working hypotheses that might be (in)validated by the research and lead to the enrichment of the theory, to its adaptation or simply, to its rejection. A design theory is at the same time, a tool for research, a conceptual framework that allows to structure research knowledge and, an object for research.

- *Design practice*: there are many design methodologies used in projects that derived from 'lessons learnt' or 'best practices' if not from the opinion of experts. In order to be able to better justify the use of one or another methodology, a scientific basis for these methodologies is required. Moreover, designers would be helped by a theoretical framework allowing them to assess in which circumstances these methodologies are valid. In addition, a design theory can help in structuring knowledge at individual and at organisational level and provide recommendations, where tools are concerned, for better supporting the designer-in-action.
- *Design education*: engineers, architects and other designers need a theoretical education that allows them to understand design in their own discipline as well in other disciplines. In a world that is changing faster and faster and where the complexity of the undertakings will require them to work in multidisciplinary teams, they will be in need of strong and well-articulated concepts to be able to understand the other and to revise, as needed, their own perspectives.

1.3 Historical context of the research

The development of theories of design in different areas started in ancient times, but it emerged as a scientific topic in the early 1960's with the development of CAD systems. During the middle of the past century, design theory in general has been most influenced by the developments in applied mathematics and system science. A first collective work on design theories was performed in 1972 (Spillers, 1974) where it was found that a big variety of approaches existed and the graph theory was the tool most used. At that time, Alexander (1964) believed in the necessity to develop a pattern theory of design: a set of steps that anyone can follow yielding a successful solution to the problem. Archer (1963) also considered design process clearly as a step-by-step process. Simon viewed design also as a teachable, methodical skill that has a systematic way to it and as a series of definite steps in practice (Simon, 1981). Rittel considered that design problems do not have definite answers, and that the process of finding the answers has to be approached differently (Rittel, 1969). Luckman (1969) proposed to decompose the design problem, based on the identification of 'decision areas'. Asimov (1962) advanced his model of the process of engineering design, which consisted of three phases: analysis, synthesis, evaluation and decision.

In 1981, a more general theory of design was developed by Yoshikawa (1981) and extended later by Yoshikawa (1988) and Tomiyama (1995), where design is described as a topological model of human intelligence. Later on, Suh proposed an axiomatic approach leading to 'good' design solutions (Suh, 1990). In parallel, other theoretical works were performed in Europe, in Australia, in Japan and in USA. Hubka (1988) developed a Total Concept Theory for engineering design known as a Theory for Technical Systems. Gero (1989), Treur (1989) and Takeda (1992) investigated the basic concepts related to the iterative nature of design considered as a process of deduction and abduction between requirements and solution. Grabowski (1995) studied a design space framework defining all possible evolution directions at a given design stage, for finding the solution.

From the beginning of 1990's, design theory has attracted more attention of various researchers in USA, UK and Canada, because of the unsatisfactory performance of available CAD systems. The notion that design is a definite process is gaining validity. The Institute for Systems Research of the University of Maryland (1990) developed an Operation Theory of Design and Manufacturing where a design axiom is proposed so as to minimise the total expected cost of design and manufacturing. Other axiomatic approaches were reported by Hazelrigg from the US National Science Foundation. Some developments on a more formal theory of design were published as well. Salustri and Venter (1992) of the University of Toronto considered a Theory of Engineering Design Information based on the axiomatic set theory and relies on it for consistency and logical rigour. Maimon and Braha (1997) elaborated a Mathematical Theory of Design to represent design knowledge and to model the design process.

Most of the past developments focused on specific aspects of design, for example, on functional, requirements, on mapping from functions to attributes, etc. Those approaches mainly deal with the early stages of design and do not cover all design phases. Furthermore, most attention has been paid to the technical issues while other dimensions like learning, organisation, human and social aspects were ignored. In other words, existing design theories are basically fragmented and consist of partially developed approaches. They have few direct (industrial) applications as they mainly deal with 'ideal' design cases.

1.4 Objectives and contributions of the thesis

The overall objective of the research is to develop a theoretical basis with generic concepts and statements for all (most) design activities. It is inspired by the existing theories and builds on them, with a consistent framework from which particular design approaches, dealing with particular types of artefacts, can be derived.

Developing a general theory of design is a huge undertaking especially when most all aspects of design have to be examined and consolidated. The specific objective of the research project is therefore to contribute to a (future) general theory of design through:
(a) The definition of a **conceptual framework** situating the main domains of design and,
(b) The development of a series of **contributions** that populate the most relevant part of this framework.

Important issues for the theory are:

- To consider design in the context of a project aimed at the realisation of some kind of artefact.
- To study design is its complex form, involving different stakeholders and where one or more designers are being commissioned to perform design.
- To deal with design as a process of knowledge construction.
- To explore as well design as a human activity, grounded in cognitive science, and explained by a series of goal-oriented cognitive processes.

The theory aimed at is not specialised in one particular type of artefacts (boats, trains, organisations, …). It is not focused on a particular professional discipline; it should be valid for non-professional as well as institutionalised design.

It is not meant to be a Universal Design Theory (Grabowski, 1998) that goes beyond the development of generic concepts and relations and that has the ambition of integrating theories of all possible domains.

To summarise, such a general theory of design aims at finding common concepts and relations between these concepts that are valid across several domains of design, allowing knowledge sharing between domains and hence, fostering communication and collaboration.

1.5 Methodology

1.5.1 Research problems and challenges

At the start of the research, following problems and challenges were considered as most important:

- *The complexity of design*. Design is complex as it deals with different people (sponsors, users and other stakeholders) having their respective views, requirements and constraints; it has to consider the artefact as such but also the artefact during the different steps in its life-cycle, including realisation, implementation, use, maintenance and disposal. One of the challenges to develop a comprehensive design theory is to take into account all those considerations in a single consistent knowledge corpus.
- *A deep understanding of the nature of the design process and its role within a project*. Some of the existing approaches mainly focus on mapping functions to physical attributes or on the steps to be performed in design. In our view, this seems too restrictive for explaining design in a wider perspective.
- *Human aspects.* Design is performed by humans supported by tools, if any. It is difficult to model and describe human mental activities during design because those activities cannot be directly observed. Even protocol analysis where designers explain what they doing, has strong limitations as expressing thoughts disturbs the design process and as the expression of mental states is far from easy. Development of a theory able to explain design ‘from project to thought’ requires drawing on contributions from cognitive science so as to identify cognitive processes used while designing.

1.5.2 The nature of the development

The notion of theory as described above provides some indications on the nature of theory development: searching for the appropriated concepts, making assumptions, exploring knowledge about design for identifying relations that are common to different design situations, summarising and abstracting and verifying and validating intermediate stages of the theory. Theory development appears to be a combination of aligning existing contributions and trying to integrate them, discovering that design topics can be explained by other domains of knowledge and that some of the concepts dealt with in design are instances of more general mental categories, and finally, designing and constructing parts of the theory into an a-priori defined structure.

1.5.3 Baseline

At the start, the baseline for the development consisted of the knowledge (at that moment) of the author, but of some basic questions to be addressed, such as:

- What is the essence of design?
- What is an artefact?
- What is the result of design?
- Who is designing?
- When designing, what happens to those involved and more specifically, what happens in the mind of a designer?
- Etc…

Obviously, like in any research activity, the answers to these questions triggered other questions and the baseline evolved in terms of accumulated knowledge. One of the difficulties encountered was the multiplicity of viewpoints and the specificity of languages proper to a given domain (Tovey, 1992).

Design literature

Design literature constituted of course an important aspect of the baseline for the development of a new theory.

The literature research deals considered all possible subjects pertaining to design: design philosophy, design thinking, design theory, design methodology and particular design methods, design organisation (how people are involved and interacting during design), design optimisation etc. The diversity of subjects and sources where potentially relevant knowledge could be found created a specific challenge.

Assumptions

A series of *assumptions* have been progressively adopted:

- Design has three connotations: design is intention, process and result. This distinction should always be kept in mind and explicitly taken into account.
- The ‘external’ perspective of a manager, a client or even of the designer taking distance from his activity, and ‘the internal’ perspective are essentially different, the former pertaining to rational models that can be made about design, the latter relating to the ‘designer-in-action’ who does not necessarily follows the plan or the method.
- It must be possible to distinguish the pure design process from the way it is executed by one designer or by an organisation of designers, in other words, it must be possible to develop a ‘functional’ point of view on design or an abstract process model that is independent from the organisation and the resources involved in performing it.
- In actual design, the level of explicitness may vary considerably. In principle, there is no need that the design (as a result) is made explicit, which is however frequently the case in professional design.
- The theory will be descriptive and hence, not deal with the definition of ‘good’ design or design performance.

- Although emotion or affects are known to play an important role in human behaviour even for the most rational designer, the theory will not deal with them, or only exceptionally.
- Although the author has an engineering background, there has to be a constant attention for using concepts that can be considered as general. The same applies to practices in engineering that are not necessarily common to other domains of design (for example, the importance given to requirements definition and management).

1.5.4 Development process

When considering the actual approach followed for the project, there was at the beginning a lot of trial and error. When including the period before the thesis project, there were distinct phases in thinking (probably influenced by the dominant paradigm of each period): design as problem solving, design as dealing with systems (referring to systems theory), design as a managed process, design as interwoven with knowledge construction and management, design as a means to cope with risk, design as a cognitive activity.

Whatever the dominant paradigm, a pattern for the project emerged:

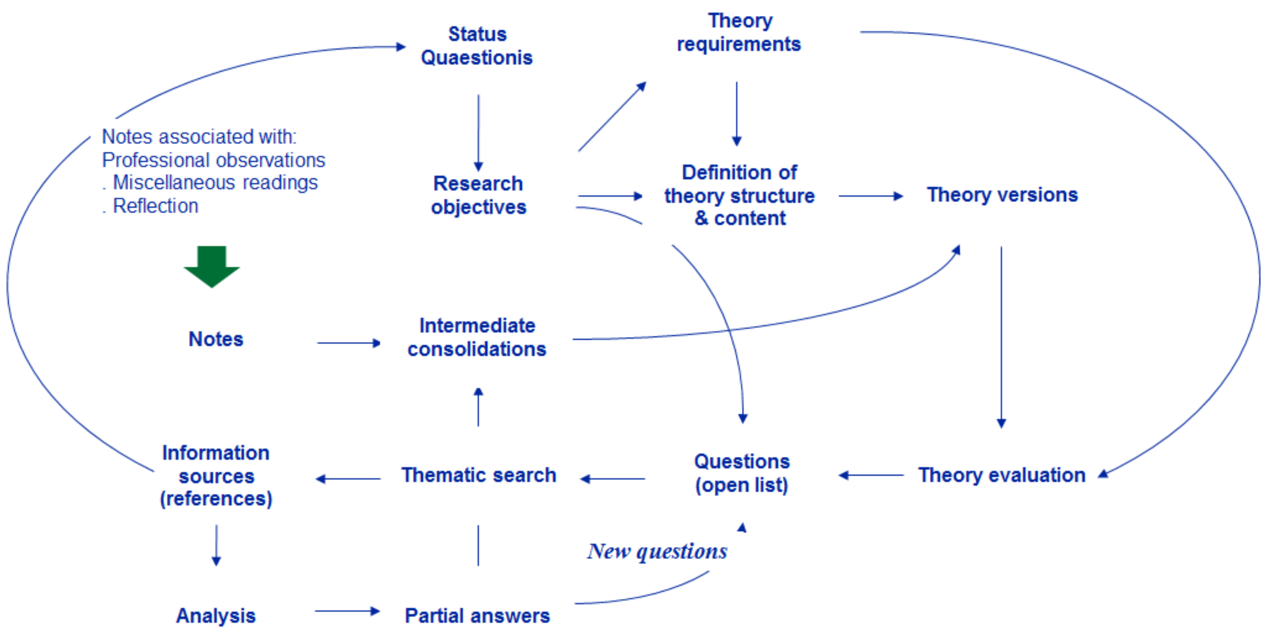

Figure 1: Thesis development process

The schema reads as follows:

- The (analysis of the) (evolving) Status Quaestionis leads to the formulation and the refinement of the research objectives.
- These research objectives lead to the formulation of questions that need to be answered. A thematic search (and sometimes, a random search) helps in identifying information sources (books, articles, web pages, contacts with people) which analysis may or may not provide the answer to the question.

- A second path for content generation consists in recording notes in all kind of situations, when interesting ideas come to the mind (by reflection and by observation) and that are recorded in the form of notes, mostly on computer. These notes (typically, one or a few A4 pages) are organised in clusters. From time to time, they are consolidated in a document that pertains to one subject. Partials answers from the thematic search are consolidated as well.
  These consolidations are helpful because they show similarities or contrasts between ideas that are close to each other, or even more, that appear to be instances of the same concept in different contexts. Consolidation leads to the emergence of concepts that are more general.
- A third path of development consists in trying to formulate requirements to the future theory and in defining a tentative structure of the theory. The intermediate consolidations are used to enrich the theoretical structure.
- The theory versions (development is an iterative process) are evaluated against the requirements and these evaluations generate new questions.

Hence, the development of the theory has resulted from three parallel paths: (1) questioning and answering, (2) reflection and observation and (3) stating ex-ante a structure for the theory. The theory emerged in successive versions that resulted from enrichment, consolidation and integration and evaluation.

1.6 The structure of the thesis

The thesis document is subdivided in following chapters:
Chapter 1 introduces the background of the research, defines the objectives and explains the methodology that has been followed.
Chapter 2, after recalling some basic concepts of design and theory, provides an overview of the Status Quaestionis and a more detailed analysis of candidate theories and confirms the need to further extend the research on general design theory.
Chapter 3 contains the actual theory of design: it comprises the framework of the theory that situates the different contributions and the contributions themselves. There are six contributions:

- The project as the context for design
- The artefact as the object of design
- The design space as the space where knowledge construction happens
- The design process as the abstract model of the design activities
- The design organisation involving people and tools
- The designer’s activities focused on the cognitive activities of a designer.

Chapter 4 is an extended case study meant to illustrate the theory and to prove the likelihood of the different concepts and of the theory as a whole.
Chapter 5 proposes a series of findings that emerged from the analysis of the theory and draws a series of conclusions and proposes a series of perspectives for the further development of the theory.
Chapter 6 presents the bibliography.

2 BASIC CONCEPTS AND STATUS QUAESTIONIS

2.1 Introduction

Before investigating and analysing the current state as to the development of theories of design, there is a need to define some basic concepts. These definitions are answers to simple questions like:

- What is design as the object of a theory?
- What is a theory?
- What are the requirements for such a theory?
- What is the theory about?

Once the concepts have been defined, and before actually developing the theory, it is necessary to examine in detail the Status Quaestionis, in an overview mode as well as by more detailed analysis of current design theories. The requirements put forward are obvious criteria to assess these theories.
It should be noticed that 'non-compliance' with the requirements does not invalidate the scientific value of what is regarded as these (partial) theories since it was probably not the intention of the respective authors to develop a comprehensive and general design theory.

2.2 Basic concepts

2.2.1 The concept of design

2.2.1.1 Definition of design[1]

The *definition of design*: in literature, many definition of design can be found that focus on the process or on the artefact being designed. Some are related to a particular domain of design, others are more general. As a starting point, the Webster Dictionary (1990 edition) formulates three viewpoints on design:

- Design as *intent*,
- Design as *process*: "To invent, to bring into being, to prepare plans, to plan in the mind, to intend for a particular purpose, …" and,
- Design as the *result* of a process: "A decorative pattern, instructions for making something, the arrangement of forms, colour, materials, the combination of parts in a whole, …".

These aspects of the definition are well covered by the definition given by (Simon, 1969) "…Design … means synthesis. It means conceiving of objects, of processes, or ideas for accomplishing goals, and showing how these objects, processes, or ideas can be realised. Design is the complement of analysis – for analysis means understanding the properties and implications of an object, process, or idea that has already been conceived."

[1] It is intriguing that in (Curl, 1999) Oxford Dictionary of Architecture, no entry is made for the term 'design'.

In the present thesis, the three connotations or dimensions of design will be dealt with: design as intention, design as process and design as the result of such a process.

Negative definitions can be given by saying what design is not.
Design is distinct from realisation. Of course, there are boundary situations such prototyping that is some cases can be considered as a part or an extension of design in others, as realisation. Another boundary condition is the following. When the medium of the design result (specification) is the same as the medium wherein the artefact is embodied, the transition between design and realisation may be hard to determine: for instance, a table of contents of a document can be considered as one of the results of the design of a document. An expanded and enriched table of contents may be considered as a more detailed design. However, the completely enriched table of contents is nearly the document itself and the exact boundary between design and realisation is not obvious. Similar situations may be found in informatics where a program is specified in an executable language.

Design is not planning. In the context of this research, planning is considered as an activity that deals with objectives, activities that are to be defined and to be sequenced and tasks to be allocated to resources and scheduled.

2.2.1.2 The nature of design

Design is a multi-faceted activity. In each discipline, for instance, architecture and engineering, design is a technical activity which means that it is related to the particular issues, technicalities and technologies of that particular discipline.
Moreover, it is obvious that design is, at the level of a designer, a mental activity and hence, a cognitive activity.
Interactions during design, between designers, between designers and managers and between designers and users and other stakeholders, are not only technical by are conditioned by the role, the position and the relative power and prestige of those involved. Therefore, design is also a social activity. In addition, it should be reminded that the introduction of new artefacts often has an impact on the behaviour of and the relations between people, which stresses the socio-technical character of design.

The qualification of the nature of design is depending on the perspective adopted. One of the perspectives less represented in design literature is the ethnographic perspective. According to Robson (2002), ethnography provides a description and interpretation of the culture and social structure of a social group. Ethnography has its roots in anthropology and deals among other subjects with the particular culture of the society being studied. Bucciarelli (1988) undertook two ethnographic studies with two separate engineering design firms; observation of the participants to the projects was the dominant technique used. The key findings were:

- All that went on within the firms was potentially designing.
- Every activity carried out within the design firms was potentially an important design act.

- Of the many members of the firms, all were potentially effective players in the design process.
- All members of the firms and those they also called upon outside the firm were potential contributors.

The ethnographic perspective appears promising for analysing design organisations and approaches involving participatory design.

In this thesis, it is explicitly acknowledged that the design is a *technical* activity (by the nature of the artefact), a *social* activity, except in the case were the designer is also producer and the single user of an artefact, because design is done by people and for people (even imagined ones) and *cognitive* activity since, design is essentially a mental activity (if prototyping is excluded). The social perspective is not fully developed, given the complexity of the subject and the limitations of the research project. Hence, the ethnographic has not been dealt with as well.

2.2.1.3 The scope of design

Although there is a whole range of disciplines that can be considered as design disciplines, including architecture, engineering, but also ‘industrial design’ (often called ‘design’, even in French, as opposed to ‘conception’), fashion design, crafts and possibly arts. The latter might be subject to discussion but an interview[2] of the artist Alechinski, one of the surviving members of the famous COBRA (Copenhagen-Brussels-Amsterdam) group indicated that at least in some circumstances artists actually perform design.
Design is dealing with all kinds of artefacts that can be imagined and potentially realised by human beings. The theory comprises a specific contribution on artefacts in order to avoid implicit hypotheses on the nature of the artefacts dealt with.

Design is not restricted to the professions to which designers usually belong: architects, engineers, industrial designers, artists. In general terms, the essence of design resides in the nature of the activity, not in the profile of the person carrying out the activity. (It is to be noticed that design performance or design success are not considered in this thesis or how good designers are designing).

2.2.2 The concept of theory of design

2.2.2.1 The concept of theory

A theory is here defined as a (knowledge) structure consisting of (a) concepts deemed relevant to describe a set of correlated phenomena and, of (b) relations between these concepts or concepts that have been derived from the primitive concepts. These relations are the theorems of the theory.

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[2] Interview of Alechinski at Klara (Flemish Radio) on 4th March 2010, Alechinski stated that he and the artist Appel were most often starting to paint without a definite idea at the start. The design or form was emerging while painting. To the contrary, Margritte started to realise his painting on the basis of a very clear idea in his mind. While actually painting he could nearly think about anything and discuss with his wife about the lunch she was preparing. These are clearly different approaches to design, the former, nearly completely concurrent design, in parallel with realisation, the latter, full (implicit) design before realisation.

A theory starts from somewhere - the baseline -consisting of primitive concepts, facts and axioms; the latter may be derived from other theories or are considered as accepted truths that have not been falsified in the past. Hence, theories can be considered as input-output structures where the input is the baseline and the outputs the theorems of the theory. The rationale of the theory is the suite of logical statements that starts from the baseline and that ‘demonstrates’ the theorems

2.2.2.2 General requirements as to the general theory of design

For the general theory we have in mind, a series of requirements are formulated. These requirements act as guidance for the development of the theory and as criteria for evaluating intermediate and final results. As the development process is never completely controlled (it is discovery, at least partially) nor even completely understood, the requirements have to be considered as tentative, in the sense that they are expected characteristics of the future theory.

In view of the overall objective of the research i.e. to understand and to explain design, a general theory should be:

- *Comprehensive*: the theory should address if not all yet the most important subjects in design such as the context for design, the relation between design and realisation, general characteristics of artefacts that can be designed, the design process in an abstract form, the organisation of the resources that carry out design and the designer considered as one of the key elements of the design organisation.
- *Explanatory*: the theory should explain design, not by referring to technicalities proper to one or more domains of design but by referring (also) to elements pertaining to more general knowledge like projects, sociology and psychology. It means explaining the more specific by the less specific. In particular, the theory should explain the relations between context, process, the result and the behaviour of a designer
- *General:* the theory should be described in terms of concepts that are abstract and generic of and not proper to one domain. The theory should be also independent as to any specific domain of design, where the artefacts, the methods and organisations or even the designer’s profiles, are concerned. The theory should also be independent as to the type of project design is undertaken for.

2.3 Status Quaestionis

The term ‘Status Quaestionis’ is Latin and means the overview and eventually, the assessment of the current situation as to a given subject. It is translated in French by ‘L’état de la question’. The expression seem preferable as compared to ‘State of the Art’ as art pertain to action (as a capability) and to form (for example, simplicity and aesthetic value) and these aspects are not addressed in this review.

For identifying the information sources, two search strategies have been followed. First an overall search was made so as to establish a baseline for the thesis project, with the focus on ‘design theory’. A series of journals have been systematically reviewed over the typical period, depending on the publication of the journal, of 2001 till 2012, leading to the examination of more than 2000 articles (The list of journals can be found in the bibliography). Of these 2000 articles, less than 600 appeared to have less or more direct relevance to the design theory and the topics dealt with. Slightly more than 30 had the term ‘theory’ in their title (including problem solving).

Another search strategy was applied: a thematic search done so as to provide a foundation to and to enrich the contributions of the theory that are developed in chapter 4. The corresponding references have been added at the end of each contribution.

2.3.1 Information sources

This Status Quaestionis raises some problems with respect to the information sources to be explored, specifically with respect to the notion of design theory is concerned (Should the Status Quaestionis be restricted to the sources explicitly defined as ‘theories’ or should it be extended to all documents that include theoretical considerations?) and with respect to the domains of design is concerned (ranging probably from arts, industrial design, architecture to engineering).

The types of literature that were actually explored:

- *Explicit theories*: (defined as such): design in general; architecture design, engineering design and other domains of design. In these domains, for instance industrial design, when theories are formulated, they deal more with the artefact than with the process or with the designer.
- *Theories in associated domains*: problem solving, knowledge management, project (management)
- *Implicit theories*: in research papers (nearly all authors working in design science have ideas on design theory), in methodologies (system engineering methodology, project management methodology) and in reference architectures such as CIMOSA and TOGAF
- *Cognition and design:* cognition science is considered as one of the foundations of design theory.

The review concerns material considered as (design) theories. To these primary sources, material examined during the course of the project and that appeared to have a valuable theoretical content has been added. What is not included is material that reflects philosophical positions about the role in society, of the designer, the architect or the engineer. The theory developed here is meant to be descriptive and hence, should be indifferent (as much as possible) to these considerations.

2.3.2 Overview

2.3.2.1 Design

Many authors refer to the De Architectura libris decem (ten books on architecture) by Marcus Vitruvius Pollio (+- 70 till 15 BC), as the earliest encyclopaedia of architectural theory, method and technology, even if these terms were not used at the time.

In more recent times, for the domain of engineering, the research on design theories emerged and expanded in the 1980’s.

An extended Theory of Technical Systems was proposed by Hubka and Eder and first published in German in 1984 dealing both with the nature and structure of technical systems as well as with the corresponding design process. A first General Design Theory was published by Yoshikawa (1981). Since then, several design theories have been elaborated, where the most known are: The Axiomatic Approach of Design (Suh, 1990), The Logical Theory of Design, represented by Takeda, Tomiyama and Treur's works (Takeda et al., 1992), The Universal Design Theory, drafted as a research project by Grabowski, (Grabowski et al., 1998), The Theory of Inventive Problem Solving known as TRIZ proposed by Altshuller (1994). In more recent work, Hatchuël & Weil (2002) developed the C-K theory which they define as a general theory of design, and Micaëlli and Forest (2003) proposed a design theory where ample consideration is paid to the analysis of artefacts while the design process is analysed at three different levels: macro level, meso level and micro level.

In parallel with the theories pertaining to engineering and architecture which frequently have material objects in mind (as opposed, for example, to software and services) two theories are worth to be mentioned given their impact on design research: The Sciences of the Artificial (Simon, 1972, re-edited several times) who saw design as one of these sciences and The reflective practitioner by (Schön, 1983), developing the concepts of reflection-in-action and reflection-on-action.

More extensive elaborations on the history of research in design science and design theory can be found in (Bayazit, 2004), (Gero, 2002), (Lossack-2002), (Hatchuel-2008), and (Proto-2009), the latter presenting major historical milestones in architecture.

2.3.2.2 Cognition and design

The origin of cognitive sciences (or science of cognition) appeared with cybernetics in the years 1940-1950. We can cite in particular the work of (McCulloch & Pitts Andler, 2004). But the development of this discipline, based primarily on interdisciplinary approaches, became only effective as from the ‘70-‘80s, particularly through the work of researchers such as (Searle, 1983), (Fodor, 1987), (Putman, 1989) to name a few.

It is difficult to accurately define the discipline. (Andler, 2004) states that cognitive sciences "are intended to describe, explain and if necessary to simulate the main provisions and capabilities of the human mind - language, reasoning, perception, motoric coordination, planning … ". Thus, the cognitive sciences have as their objective, through interdisciplinary approaches, to model as well as to simulate the cognitive functions i.e. the processes that deal with the acquisition and the use of knowledge. The interdisciplinary character implies a dialogue and exchange of knowledge, analysis, methods between two or more disciplines. It implies that there is interaction and mutual enrichment between different specialisms (Nissan, 1996).

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 helps 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 incorporating 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. In view of the literature, some cognitive functions appear to account for the major cognitive process developed during a design activity:

- The development of knowledge and the construction of mental representations (Meunier, 2009), which was already indicated by (Visser, 2006) as being essential in design,
- In memory processes, two components appear to be relevant: the working memory (Baddeley, 1996) that allows the manipulation of various forms of temporary representations and the semantic memory (Tulving, 1995) that belongs to the long-term memories that store all of our knowledge.
- The concept of metacognition introduced by (Flavell, 1979) provides an understanding of the importance of our own knowledge of our knowledge, "know that we know." Metacognition is knowledge of one's own cognitive activity or that of others, which allows the planning and control of it during the reporting (Metcalfe & Dunlosky, 2009) and (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) and (Rozencwajg, 2003).

There are different approaches to cognition in design but there is presently 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 a 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.

2.3.3 Review of the main sources

C. Alexander. Notes on the synthesis of form. 1964. The kernel idea of this book is about “diagrams” or “patterns”. The author defines them as “abstract patterns of physical relationships which resolve a small system of interacting forces, and that is independent of all other forces, and of all other possible diagrams. The approach is oriented towards the structure and the form of an artefact. It can be brought in parallel with ideas of Bauhaus, of modularity and the notion of re-use of solutions (which is also found in biology).

G. S. Altshuller. Creativity as an exact science. The theory of inventive problem solving (TRIZ). 1988. See also (Souchkov, 1998). The publishing date is misleading as Altschuller started in the late ’40s and ‘50s, in the former Soviet Union, with the development of his theory. The TRIZ method that includes the theory, evolved over the years but the basic concepts remain stable. A first important concept is the problem solving process than is not simply trial and error in terms of finding a specific solution for the

specific problem at hand, but that requires making an abstraction of the specific problem, that solves the abstract problem and then that moves to the specific solution.
The theory recommends also taking into account technology evolution for the same family of objects which are formulated into eight laws. The part of TRIZ that is the most known is probably the set of forty inventive principles. Design problems are considered resulting from conflicts or contradictions between requirements or artefact properties, most often at artefact level; inventive principles can be applied using a matrix for engineering contradiction elimination. TRIZ is not a coherent theoretical framework; it contains elements of theory and also a series of practice-derived principles and laws. It belongs to the domain of engineering design. Extensions to business problems and software engineering are being developed.

M.M. Andreasen M.M. The role of artefact theories in design. 1998(a).The author illustrates the complexity of design and the themes a theory of design has to deal with: activities, artefact, product life-cycle, goals, tasks, resources In trying to define a ‘good theory’ as “the ideal development of a scientific result in this area is the crystallisation and structuring of a theory, its transformation into methods and techniques, fitted and mediated for the user, and implemented, utilised and followed up in the industrial enterprise” he addresses obviously design in professional situations and in for-profit contexts (enterprises). Andreasen argues that an artefact theory should be part of a universal design theory and be articulated on the rationale: ”… structure determines behaviour, structure is described by design properties, behaviour is functionality and properties…”. He sees the theory involving three structural views: transformation system (cost, time, quality, efficiency, flexibility, risk, environmental effects), organic system (reliability, liability, low cost, ergonomic properties, low noise, …), parts system (strength, surface quality, tolerances, material properties, ….). According to him, universal design theory aims at bringing different theories together, integrating and integrated in a common interrelated pattern with an all-round applicability.

N. Cross Engineering design methods. 1989. The author is in line with the position of Simon in stating that design problems are ill-defined problems because (a) there is no definitive formulation of the problem, (b) any problem formulation may embody inconsistencies, (c) the formulation of the problem is solution-dependent, (d) proposing solutions is a means of understanding the problem and (e) there is no definitive solution to the problem. He proposes a basic design method consisting of a series of steps: clarifying objectives, establishing functions, setting requirements, generating alternatives, evaluating alternatives and improving details. The theory refers to the problem solving approach. In addition, an inventory is made of specific methods (which could be called ‘techniques’ that support the designer in carrying out his design task.

N. Cross, H. Christiaans & K. Dorst. Analysing design activity. 1996. This is not a book on theory but it is important because it deals with an approach that tries to determine what happens actually during design by applying protocol analysis. It reflects findings made at the occasion of the second Delft Workshop on Research in Design Thinking II – Analysing Design Activity. The objective was to make in-depth observations of designers at work, novices and experts, of the nature of the activities carried out, of the design strategies applied, of the use of knowledge, and of the interactions within a team. There are actually limitations to the information that can be extracted from protocol analysis: any expression of thoughts is modified by the 'channel' used (verbalisation, gesture, written expression), by the formalism, if any, and even by social factors. In most cases, people often express only what is considered socially acceptable. On the other hand, thoughts occur at such a high pace, in other words, the content of the short term memory has a degree of volatility that the expression of only a part of what has been thought.

R. Focqué. Building knowledge in architecture.2010. The book presents another approach to design. From a methodological viewpoint, it compares design with science and art and states that "science is about how things are, design is about how things could be and arts about how I (the artist) see things". Design is a creative, a structuring and a communicative activity. He proposes a knowledge framework articulated around design (a) context, (b) function and form, (c) build, with the subthemes domain of construction, domain of engineering and domain of materials and (d) occupy (use), with the subthemes sustainability, flexibility and user perception. It refers clearly to architecture. The author appears to hesitate between an architect(ure)-centred position to a more general position that goes beyond the domain of architecture. The notion of knowledge framework can be considered as a useful complement to a method or process approach to design.

J.S. Gero. Towards a theory of designing as situated acts. 2002. The author adopts the notion of situatedness that "includes the notion of interaction (of the actor) with the environment and the notion of where you are when you do what you do matters. The situation is a construction based on the interpretation of the external and internal environments in relation to the expectation of the designer". In this perspective the author proposes the FBS framework where F stands for function, B for behaviour (the distinction is made between expected and actual behaviour, the latter being determined by the structure) and S for structure. For all designing, following processes are claimed to be fundamental: formulation, synthesis, analysis, evaluation, documentation and reformulation. These processes are in fact transitions between the components of the FBS framework. There is no clear relation between the FBS framework and the situatedness of the activities.

G. Goos. Systematic software construction. 1998. This work pertains to the domain of software engineering and it is mentioned because it is representative of a prescriptive approach to design. The author adopts the VDO Process model standard (VDI 2221) that defines the (standard) steps of a project: feasibility study, system development, system production, system introduction, system use and system change. Each step is subdivided in: problem analysis, problem definition, synthesis, system analysis, and decision. The proposed methodology combines project-related activities with problem solving activities. The theory is prescriptive and not particularly aiming at explaining design.

H. Grabowski, S. Rude and G. Grein (eds). Universal Design Theory. 1998. This book results from a workshop in Karlsruhe in May 1988 that dealt with the concept of Universal Design Theory, in principle, in the domain of Engineering Design. Among the many contributions, there is the paper developed by the editors together with E. Meis and E-F Mejbri on Universal Design Theory. The distinction is made between …”(a) theories of design such as the ones by (Suh, 1990) and (Yoshikawa, 1987) that try to explain the nature of technical products and to find a procedure of general validity for the invention of heretofore unknown artefacts and (b) a Universal Design Theory that not only encompasses generic, discipline-independent knowledge, but also discipline-specific knowledge about design”... Such a theory also describes the interfaces with the different disciplines (of engineering design). There are two problems associated with the establishment of this theory: the problem of universality and the problem of applicability. The first is to be solved by the development of a common design language, the second by the detailed analysis of the requirements and by the mapping of these requirements on the design solution. The theory is quite ambitious and in comparison with it, this thesis focuses on common elements in design domains without including domain-specific elements.

A. Hatchuel & B. Weil. Entre concepts et connaissances: éléments d’une théorie de la conception. 2002 and 2008. The authors argue that there is a fundamental difference between knowledge and concepts. The C-K theory 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) expand the concept-space, (c) expand the knowledge-space and (d) 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. The C-K theory remains very open as to the object of design and as to the nature of the concepts to be developed so as to achieve a design specification. The C-K theory is compact and elegant but quite general and seems to be valid for many activities such as planning, modelling, simulation, problem solving. In that sense, it might be a theory of goal-oriented thinking. The C-K theory does not establish an explicit link with cognitive processes. From a cognitive perspective, the position of fundamental difference between concepts and knowledge could be invalidated. An open question is whether by concepts as used in the theory refer to verbalised knowledge or whether other forms of knowledge (cognition) are considered. In addition, from a cognitive perspective, concepts are also knowledge and therefore, the specificity should be explained in cognitive terms.

V. Hubka V. & W.E. Eder. Theory of technical systems. 1988 (first edition in 1974). Hubka was among the first to recognise the need for explicit theory of technical systems. The theory focuses on the commonalities between technical systems (tangible and process). The authors recognised that design engineering is a combination of capabilities: scientific knowledge, skills (design as an art), knowledge and experience, heuristics and creativity. The theory of technical system is mainly artefact (technical system) oriented and aims at identifying all modes of action of a technical system determined by the modes of action of its components, each mode of action being governed by an action principle. Although the experience of the authors was essentially in mechanical engineering, they tried to be as general as possible in their descriptions. The theory of technical systems was later accompanied by a Theory of design processes (1976) which combines a problem solving approach with their theory of technical systems life-cycle.

R.S. Lossack Foundations for a universal design theory. 2002. This paper has been developed in the perspective of a universal theory of design. It syntheses key elements of a process approach to design: (a) the stepwise approach in a general problem solving cycle (problem definition, solution finding, solution description, solution evaluation and the solution selection), (b) aspects of design (product requirements modelling, function modelling, physical principle modelling, embodiment). It develops the notion of object patterns as well as process patterns and it uses the concept of design working space where the object is to be found. The design space has boundaries where inputs and outputs are exchanged. The notion of design working space is somewhat confusing: is it the imaginary space where the future object can be found within its context or is it a virtual representation of the object alone or even, is it the space were all design knowledge resides? The proposed notion of object pattern can be brought into parallel with the views of Alexander.

Micaëlli & Forest. Introduction à une théorie de la conception. 2003. In their introduction to a theory of design, the authors argue that different perspectives can be adopted with regard to design. The corresponding roles are: the physicist, the automation specialist, the mechanical and the production engineer, the manager and the economist. They explore also the different levels for examining design: the macro level that is focused on the context for design, the meso level where considerable attention is paid to the design process and the micro-level dealing with the interactions between designers, between designers and activities, between designers and artefacts. The authors introduce also a typology of design projects: inventive project, innovative project, construction project with routine design and redesign project. The work of Micaëlli and Forest is actually an introduction rather than a normative theory and explains the main themes that constitute a theory of design. In our view it belongs to the domain of design philosophy.

Pahl & Beitz. Konstruktionslehre. Methoden und Anwendung. 1997 (first version in 1984). This theory focuses on the design process that according to the authors consists of a series of problem solving activities for the following steps: “Aufgabe” (mission statement for the design project), “Planen und Klaren der Aufgabe” (planning and elicitation of the design project), “Konzipieren” (concept design), “Entwerfen” (realisation design in the sense of embodiment), “Ausarbeiten” (detail design) and “Lösung” (finalisation and solution of the problem that triggered the design project. The theory is rather prescriptive and is strongly design methodology-oriented.

D. Schön The reflective practitioner. How professionals think in action. 1983. This book is not a design theory but it is important as it shows the behaviour of professionals during their work. The principles are based on much earlier research of human learning and development. Schön states that “reflective practice is the capacity to reflect on action so as to engage in a process of continuous learning” which appears to be one of the defining characteristics of professional practice. Indeed, design is a knowledge and cognition-intensive and the design process is accompanied by a parallel learning process. This approach can be related to Simon (problem solving) and Gero (designing as situated acts).

H. Simon. The sciences of the artificial. 1981. This seminal work had a strong influence on later authors involved in design research. The book that has been re-edited several times, deals with the sciences of the artificial as opposed to natural science. Design is considered to be one of these sciences such as economy or social planning. Design is specifically involved with creating the artificial. Design is considered to be (an application of) problem solving involved in the solution of wicked or ill-defined problems i.e. problems whereby the solution affects the understanding of the problem. Solutions are not "true-or-false" but "good-or-bad" and conditioned by a satisficing criterion. Simon stresses the importance of domain-orientation ("The smartest people in the world do not generally look very intelligent when you give them a problem that is outside the domain of their vast experience.").
For designing a complex structure, one powerful technique is to discover viable ways of decomposing it into semi-independent components corresponding to its many functional parts. The design of each component can then be carried out with some degree of independence of the design of others, since each will affect the others largely through its function and independently of the details of the mechanisms that accomplish the function. He proposes a definition of the designer that implies also a quite extended scope for design itself: "…(a designer is)…. Everyone designs who devise courses of action aimed at changing existing situations into preferred ones. The intellectual activity that produces material artefacts is no different fundamentally from the one that prescribes remedies for a sick patient or the one that devises a new sales plan for a company or a social welfare policy for a state". The weaker point in the theory seems to be the minor importance given to the types of artefacts as well as to the aspect of (mental) representations that accompany design.

N. Suh. Axiomatic design principles. 1990. The theory is a general theory but of a limited scope. Its aims at prescribing fundamental design principles: functional independence (maintain the independence of the functional requirements) and minimal information (minimise the information content of the design. These principles are stated as axioms. The axioms are essentially applicable to the object of design: the artefact. The design process consists in ensuring that the axioms are applied. If the axioms of functional independence can be understood in a perspective of modularity, there is still an open question about the universal applicability of the minimum information axioms: is this axiom verified in the context of industrial design where complicated forms do not necessarily correspond to minimal information content?

Tomiyama & Yoshikawa. Extended general design theory. Design theory for CAD. 1987. The General Design theory developed by Yoshikawa & Tomiyama pertains to the domain of engineering design and it uses set theory and topology for modelling design knowledge and the design process. Although it is limited to the study of idealized design processes with a perfect knowledge structure (topology), it does contribute to a better understanding of the process of designing and the structure of design knowledge from a cognitive point of view. It pays considerable attention to the mapping of functional requirements to physical attributes. The overall design process follows a problem solving logic.

W. Visser. The cognitive artefacts of designing. 2006. This study could be considered as a theory of design cognition. It stands in contrast with or in complement to the approach taken by Simon: design is more than problem solving, it is also about the construction of cognitive representations, which can be of all types: perceptual, verbalised or not, etc…The author refers also to the designer-in-action dealing with concrete, situated design problems. The author refers also to the notion of cognitive cost, which acts as a criterion for decision making. When facing alternative paths of action, the designer will select the option that appears to be the most ‘economic’ from a cognitive point of view, in terms of processing effort. This explains the opportunistic behaviour of designers. We would prefer the notion of (expected) cost versus the (expected) benefits of a course of action. On the other hand, it might be questioned whether cognitive cost is the sole criterion.
The book is not very specific about the nature of the representations that have to be made so as to achieve ‘good’ design.

2.3.4 Other sources

Buchanan & Margolin

These authors published several works and among them, *Discovering design, 1995* and *The designed world, 2010*. These works, both collections of papers that have been published earlier, are not to be considered as theories of design but rather as contributions to a philosophy of design that might provide the meta-theoretical framework for a theory of design. Themes dealt with are: conceptualisation and shaping the object, the world of (design) action, the design process and new domains of practice (the impact of information technology on design), the social meaning of things, values and responsibilities.

H.F. Mallgrave

Architectural theory. 2006. This is an anthology of architectural theory published in two volumes: Vol. I An anthology form Vitruvious to 1870 and Vol. II An anthology from 1871 to 2005. It contains a series of papers mostly about the ideas of architects on the most various topics pertaining to architecture, the philosophy of architecture and architecture education. The book is more an encyclopaedia of architectural research and theory over the years rather than an integrated theory.

2.4 Findings

The theories and other contributions have been assessed:

- As to the domain of applicability
- As to the subjects they address according to (Dorst, 2007): context, object, process and actor.

The overview is given in the table below:

Theory	Design domains				Theory topics covered			
	All	Architecture	Engineering	Other	Context	Object	Process	Actor(s)
Alexander (Notes on the synthesis of form)	-	X	-	-	-	X	(X)	-
Altschuller (Creativity as an exact science)	-	-	X	(X) a	-	(X)	X	-
Andreasen (Artefact theories)	-	X	X	-	-	X	-	-
Cross (Engineering design methods)	-	-	X	-	-	(X)	X	-
Cross , Christriaans & Dorst (Analysing design activity)	-	(X)	X	-	-	(X)	X	(X)
Focqué (Building knowledge in architecture)	-	X	(X)	-	(X)	X	X	(X)
Gero (Design as situated acts)	-	X	X	-	-	-	-	-
Goos (Systematic software construction)	-	-	(X)	-	-	(X)	X	-
Grabowski (Universal Theory of Design)	-	-	X	-	-	(X)	X	(X)
Hatchuel (C-K theory)	X	X	X	X	-	(X)	X	-
Hubka & Eder (Theory of technical systems)	-	(X)	X	-	-	X	-	-
Hubka & Eder (Theory of design processes)	-	(X)	X	-	-	-	X	-
Lossack (Design process)	-	-	X	-	-	-	X	-
Micaëlli & Forest (Introduction à une théorie de la conception)	(X)	(X)	X	(X)	(X)	-	X	-
Pahl &Beitz (Konstruktionslehre. Methoden und Anwendung)	-	-	X	-	-	(X)	X	-
Schön (The reflective practitioner)	(X)	(X)	(X)	(X)	X	-	(X)	X
Simon (The sciences of the artificial	X	X	X	X	-	-	X	(X)
Suh (Axiomatic design)	-	-	X	(X)	-	X	(X)	-
Tomiyama/Yoshikawa (General theory of design)	-	-	X	-	-	(X)	X	-
Visser (The cognitve artefacts of designing)	(X)b	-	-	-	-	-	-	X

(a): Extensions are being developed for business systems and software engineering
(b); Valid in principle for all domains but influenced by the context wherein the theory has been developed (mechanical and software engineering)

Table 1: Comparison of design theories

The four main findings emerge from this assessment:

- *The scope of the theories.* Existing design theories have significantly contributed to a better understanding of design. However, for most of the theories their scope appears to be limited as they deal only with some aspects of design: as said before a lot of focus on the design process. One of the explanations could be found in the fact the designers are more 'doers' than 'thinkers'. Moreover, in view of the immense diversity of artefacts that may the object of design, they tended to find invariants in the design process so as to get better control of their design activity. In the more recent years, however there is much more attention to design cognition. This is probably due to the expansion of cognitive science and the progressive awareness that the notions of cognition content and cognitive processes may help to explain in greater depth what happens during design.
- *(The lack of) general character of the current theories.* Most theories refer explicitly to professional design and to a limited set of domains, mainly architecture and engineering. There is a risk to introduce in the theory a series of assumptions that are specific to these domains, for example, about properties of the artefacts (technical or physical) or about the context wherein design is taking place (professional, teamwork, competitive commercial environment). These assumptions strongly limit the general character of the theory. The mono-designer situations are far from worthless. It has to be noticed that there are examples of sole inventor-designers who developed a successful product on their own, outside their normal working context and without a clear mission statement from their organisation. Such cases are also cases of design (and realisation) and have also to be explained by a general theory of design.
- *Perspectives on design.* Most of the theories are strongly inspired by a dominant perspective: design as problem solving (e.g. Simon), design as a process (e.g. Altshuller, Lossack), design as a situated activity i.e. strongly context-dependent (Gero, Schön), design as dealing with artefacts (Andreasen, Suh) or design as a cognitive activity (e.g. Visser). Hatchuel proposes a theory that is nearly mathematical (relating to set theory) and that in our view goes beyond the scope of design. The present version of the theory is quite general but does not refer at all to the context wherein the

process is taking place. Nor it does elicit the specificity of design as compared to problem solving or planning.

- *No process model or method for theory development.* In nearly all cases the theories examined did not provide indications on how they came into being.

2.5 Conclusions

1. When assessing the adequacy of the theories against the requirements put forward in chapter 2 i.e. comprehensiveness, explanatory character and generality, the conclusion is that no theory of the ones reviewed fulfils the three requirements.
2. None of these theories provides an integrating framework that allows situating the different design theory contributions that might facilitate if not their integration, at least their alignment.
3. The need for a general theory of design remains.
4. There is no need to modify the methodology followed for this research project.

3 CONTRIBUTIONS TO THE GENERAL THEORY OF DESIGN

3.1 Introduction

As stated in the introduction, the present research project aims at proposing a series of contributions to a general theory of design. The contributions would be rather meaningless if there were not situated in a framework that shows the relationships between the different parts of the theory. This framework could later evolve towards an extensive conceptual model for design whereby the theory acts as the associated rationale that explains and justifies the conceptual model.

Section 3.2 introduces a framework for design theory. This framework identifies main theory elements and relationships between those elements. Sections 3.3 to 3.8 present the framework elements that contribute the proposed design theory.

3.2 A design theory framework

Design is a complex phenomenon and the diversity of specific design instances in all types of projects is ended-less. A considerable number of variables are influencing design and in order to reduce complexity, it is worthwhile to investigate whether these variables can be regrouped in sets where the variables belonging to one set are tightly bound to each other and where the variables belonging to different sets are (more) loosely bound.

Most often, design is a part of a larger endeavour – the *project* **-** that leads to change, in particular, to the modification of an existing situation and for the projects that are interesting for the present research, to the realisation of one or more new artefacts. Projects can be undertaken by individuals, by groups of people, by organisations or even by groups of organisations. Projects act as the operational context for design: there are activities that come before design and other activities that follow. Design has a specific role to play in a project that will be explained later.
It must be noticed that a project itself is embedded in a project context that has often a technical, an economic, a social and a cultural dimension.

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 form the subject of design. They are extremely diverse, ranging from technical objects such as consumer products and investment goods, or symbolic objects (for example, an obelisk), to virtual objects that have to be 'animated' (like a web page or a movie) or executed by a resource such as computer program or a business process. It is obvious that during design attention must be given to the nature of the artefact that one wants to see realised at a given moment.

The design activities in a project are influenced by the project and by the nature of the artefact and also by the set of means (the design organisation) that execute these activities. Making abstraction of these influences and trying to identify the design activities, leads to the notion of *design process*. It is the neutral set of activities that constitute the essence of design. The design process is a model that, given the specific circumstances of the project, is to be instantiated for that specific project.

As will be shown in the contribution on projects, the design process is essentially a process of knowledge construction about the artefact: in the widest scope of the design process, it is about the artefact as such, about its realisation and about its expected life-span until disposal. It is assumed that this knowledge construction happens in a virtual space, the *design space*, which in reality can take different forms: the mind of the designer, a black board, a computer. Similar to the notion of design process, the design space is an abstract concept.

When considering the people and the resources involved in design, they, together, execute the design. In other words, given the project intent and the type of artefact that is aimed at, they instantiate the design process and the design space. Together they are defined as the *design organisation* whereby it is understood that it means the whole set of people and resources (including explicit knowledge) involved in design and not simply the organisation structure i.e. the relations between these different resources. In other words, the design organisation is the set of resources (human, technical and knowledge resources) assembled for executing the design process.

If we want to further understand design, it is necessary to consider the *designer's activities*; in the end, it is the designer who, by carrying out a series of activities, cognitive and other, actually performs design. Depending on the case, he will do this alone or in collaboration.

The identification of the sets of variables that influence design, leads to of a framework for the theory. It takes the following form:

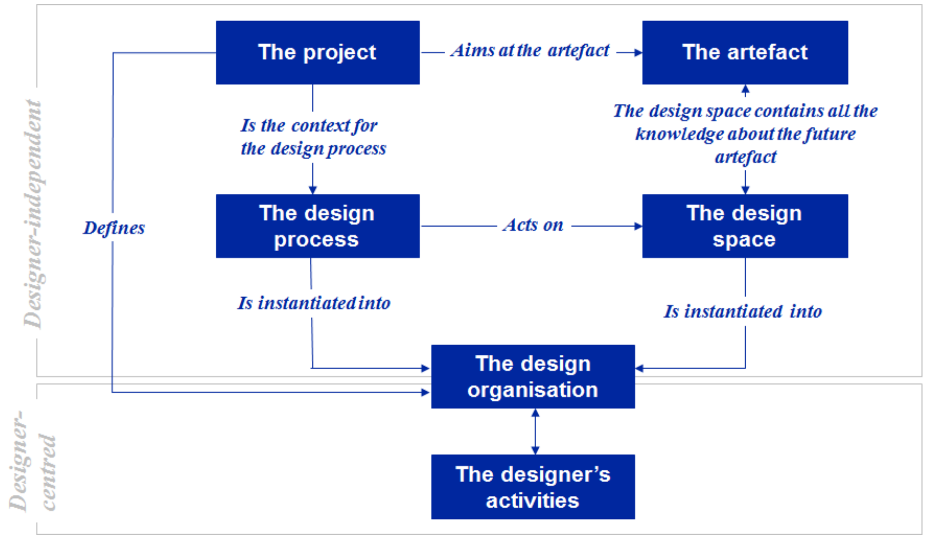

Figure 2: Theory framework

The framework reads as follows.
The project defines the goal and more specifically, the artefact to be realised, and leads to its realisation and implementation.
The design space contains at any moment all the knowledge about the artefact. The design process as a knowledge construction process (this will be explained later) acts on the design space. It is the design space that the knowledge is constructed. The project is the context wherein design happens. Design is only a part of the project activities.
Both the design process and the design space are abstract notions and to become real have to be instantiated i.e. enriched with contextual information pertaining to the particular project and a particular artefact and to the resources (people and tools) needed for executing the design activities and for providing a medium for the design space.

The designer's activities are in principle part of the design organisation but they do receive special attention in order to allow the explanation 'from project to thought' or from 'project intent to cognitive design activity'.

The different parts of the framework form the different contributions to the design theory. Important to notice is the fact that the sections about the design organisation and about the designer's activities are partially developed because the full development of these contributions goes beyond the scope of the present research project.

The contribution on the design organisation addresses the instantiation of the design process that for a given project translates into one or more design tasks which are allocated to the available resources. However, the impact that the nature of the design organisation, its structure, its culture, may have on the design tasks and on the design results is only approached in general terms. A full development would require the investigation of team and organisation behaviour in the context of design.

Similarly, the contribution about the designer's activities, although it identifies the different types of interactions and activities a designer may be involved in, is focused on the cognitive activities and does not develop in-extenso the other activities such as the expression of the design results, the communication and collaboration with other designer's, the interaction with tools, etc…This limits the scope of the current version of the theory. The focus is justified by the definite need to understand the cognitive behaviour of the designer so as to develop a basis the analysis of the behaviour of design teams and design organisations.

3.3 The project as the context for design

3.3.1 Introduction

Design does not stand alone. In most cases, what most people are interested in is not so much the specification of the future artefact but rather its realisation, its existence, its use and the impact of its existence. Hence, design as an activity has to be considered in the (operational) context of the endeavour (the project) that aims to actually realising and using the artefact. In exceptional cases however, a project can be limited in scope and focus for example on exploratory design, experimental design, design competition or on design training, i.e. only on the design activity.

It is important to notice that in the present research, projects are considered a goal-oriented action, aiming at a desired transformation. Projects do not necessarily belong to the professional realm: individuals as well as laymen can undertake projects.

3.3.2 Related work

In most of existing design theories, the notion of project is not explicitly addressed except in the cases where the theory proposes a methodology that subdivides the project in phases.

A description of the main concepts pertaining to projects can be found in the appendix. Sources on project methodology are much more numerous and diverse that on project theory, although these methodologies often refer to principles and assumptions that could be subject to theory formation.

Very often, project methodologies do imply a certain level of theoretical thinking but it is not necessarily explicit. One of the standards works on project management (relating to practice) is the PMBOK Guide (PMI-2008), (Reich, 2006) and (Zwikael, 2009) or Prince2. The former is a ‘Body of Knowledge’ for project management encompassing a series of processes and rules for project management that act as knowledge resources for the project manager in charge of planning and control of his project. Prince2, is a de facto standard, developed and extensively used by the UK government. It is actually a methodology involving a generic process model for project and a collection of standards and rules. It is considered as a generic best practice for project management. One can find in these references an extensive description of the project management concepts.
The process models are intrinsically focused on professional project. It is up to the decision and the discipline applied by individual agents to use them a simplified form.

In project management, one of the main concerns is to manage the project with a defined scope, within a given budget and within a given time-frame. If we consider the whole project life-cycle including design, this holds some kind of contradiction because a project has to be realised within a given time-frame and a given budget while specifically, during design the scope of the project is defined and refined. In routine design and realisation, such as in civil engineering for traditional buildings, it may be possible to succeed in respecting the three constraints (scope, time and budget) but it is certainly not always the case in innovative projects.

In their critique of project management theory and assumptions, (Lenfle, 2010) and (Koskela, 2002) concur in stating that in current project practice, there is too much an emphasis on control over flexibility and innovation and therefore, more attention should be put on iteration between design, prototyping and testing, and on knowledge development. Risky activities should be dealt with in a separate manner as compared to routine activities. This is an important point to take into account as the project determines the design activities.

3.3.3 Key concepts[3]

The notion of *project* pertains to the set of actions that are required to perform an intended change for the people involved or for their environment. Conversely, a project is the implementation, through a series of actions, of a given intent. Projects distinguish themselves from continuous action for they are, in principle, to be limited in time[4]. Projects are one form of production, other forms being process production or job-shop (discrete) production.

The *intent* of a project may be associated with a target situation to be reached but it may be also focused on the process itself, for instance, for entertainment, exploration, learning and/or playing purposes. The intent is the intent of the project sponsor or the consolidated intent of the stakeholders in so far they have a direct influence on the start and management of the project.

The notion of *context*: as related to an object under consideration, the context may be defined as the set of elements that do not belong to the primary focus of attention (the object) but that nevertheless are deemed important for describing the object and its behaviour and to explain it.

Most often, especially but not uniquely in the professional domain, a project is undertaken in:

- A technical context involving artefact technology, realisation processes and resources, design methods, standards and tools,
- An economic context involving costs associated with design, realisation and operation, and economic benefits derived from the existence, the operation and ultimately the disposal of the artefact,
- A social context involving the nature of the relations between the agents directly and indirectly involved, the structures of the socio-technical systems they are part of, the political system they are in,

[3] A series of concept that pertain to the notion of project are detailed in appendix 6.1. Only those concepts that are more tightly related to design are described in the present paragraph.

[4] It should be noticed that the above is in line with Western philosophy with a “linear” view on transformation having a start and an end and whereby a transformation can be relatively isolated from another one. In Oriental philosophy, there is as stronger tendency to consider change as being cyclical.

especially in the case of major institutional programmes like the moon programme or defence programs during the Cold War, and,

- A cultural context involving the beliefs and values of the society where the transformation is taking place; this cultural context involves also the status allocated to agents such as entrepreneurs or designers, the norms applied and the status attributed to an artefact (for example, the innovative character of an artefact). In present times, major attention is increasingly paid to the ecological environment. These different contexts determine among other the decisions made about the artefacts that are designed and about the design process.

Taking into account the complexity of these contextual elements and the limited knowledge at the start of the project, the *uncertainty* about the project itself, about the results to be achieved and about the consequences of the project, may be such that no immediate action (realisation) is undertaken. Reasons for realisation postponement are: uncertainty as to the precise type of artefact, as to artefacts purpose and its required capabilities, uncertainty as to artefact embodiment (which structure and which materials), uncertainty as to the realisation of the artefact and the resources needed (type, quantity, capacity), uncertainty as to later phases in the artefacts life-cycle, etc…..In short, there is uncertainty related to the one-time character of a project.

3.3.4 Rationale

Three important issues have to be addressed about design and projects:

- The role of design in a project
- The position of design as a set of activities, among the other project activities and, to summarise,
- The relation between project and design, or how the project determines the design to be done.

3.3.4.1 The role of design in a project

When one knows what to do and one can do it, action (realisation) can be immediately started. In the other case, the realisation is postponed and preliminary activities are undertaken. These preliminary actions are aimed at (a) knowledge construction so as to reduce uncertainty and (b) assembling and organising the resources needed.

These preliminary knowledge construction activities can be organised in phases or may be informal. For one person, these pre-realisation activities are essentially of a cognitive nature. In teams, these actions are called research, studies or preparation work, for example, technology investigations. The activities can be differentiated by the specific aim they pursue:

- Oriented/applied research: developing knowledge in areas that appear to be relevant to the anticipated project.
- Goal definition: defining the goal for an action to be undertaken.
- Problem solving: analysing a problem that requires action, identifying the possible alternatives for solution, and selecting the solution to be retained.
- Designing: specifying the artefact to be realised and to be implemented so as to contribute to the realisation of the TO BE situation.

- Planning: defining a course of action (a sequence of activities to be performed), identifying the required resources and allocating the activities to resources.
- Simulation: What-if analysis on the basis of scenarios.

These considerations lead to a definition of design in reference to its nature and purpose. The purpose of design is knowledge construction, specifically about each artefact to be modified or created, so as to reduce the uncertainty pertaining to the later phases of the project and to the whole life-cycle of the artefact or its instances.

(Regev, 2006) has on more 'defensive' view on uncertainty, as he talks about risk. He identifies risk as 'knowledge gaps', confirming the need to fill these gaps.

(Zhang, 2011) discusses two schools of risk: the one considering risk as an objective fact, the other as a subjective construction. The position taken in this thesis is that when considering the sole designer, risk is a subjective construction. For teams, it becomes an inter-subjective construction. For the whole project, especially when risk is analysed via explicit methods, it tends to become more and more objective. However, the attitude as to (subjective) risk of the people involved is still important.

Ullman (2003) illustrates (for mechanical design) the evolution over time of the reduction of degrees of freedom and the growth of knowledge about the design problem (and about the solution: the artefact):

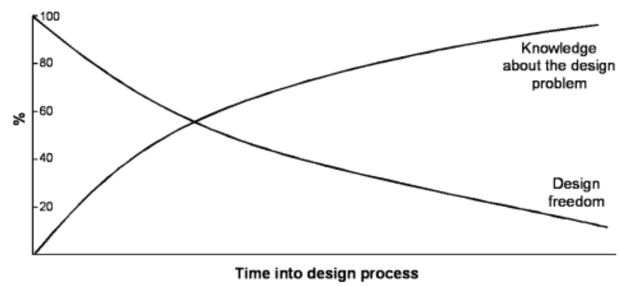

Figure 2. Schematic depiction of how knowledge/information about the design problem accumulates during the progress of the design process, and how the degree of design freedom will decrease at the same time (Ullman 2003).

Figure 3: Evolution of design knowledge and of the degrees of freedom (Ullman, 2003)

This above definition of design could be called 'functional' definition in the sense that it defines the role or the function of design in the context of a project.

Uncertainty is not restricted to the notion of risk: it is also related to the reduction of the number of degrees of freedom pertaining to the artefact: when all degrees of freedom remain undefined, all alternatives are open.

In this perspective, one can 'over-design' in the sense that too many characteristics of the artefact are determined while more flexibility in realisation or in use might be required.

An example in the area of information systems dealing with data-bases is the following. In answer to the formulated needs of the users, a designer may define a discrete number of transactions for inquiring a data-base. On the contrary, he could design a tool for formatting queries as considered by a user, in various situations. The first approach could be considered as over-design by limiting the number of transactions and hence, by fixing too many degrees of freedom.

It should be noticed that the design process reduces uncertainty but does not eliminate it completely. There is still uncertainty associated with the actual realisation, the use by users or the appropriation by the target audience, with the reliability and the maintenance and even with the actual disposal of the artefact.

3.3.4.2 The position of design in a project

It is important to distinguish the design phase from the design process:

A *design phase* is a set of activities carried out at a given moment, in a project, involving among others, design activities. Design phases carry many names: system design vs. component design, preliminary vs. detailed design functional vs. technical design, etc…A design phase naturally encompasses design activities but most frequently, also planning and follow-up for the phase at hand, planning of the subsequent phases, justification of the project on the basis of the design, planning and risk analysis activities and production of milestone reports. Hence, a design phase is more than only design; it is a sub-project.

The *design process* is an abstraction: it is a process model that logically links the different activities each to each other. Design is about the artefact and involves essentially the definition of the artefact, the specification of its properties in the perspective of realisation, the anticipation of its realisation and the anticipation of its complete life-cycle. Most of the design activities are carried out during the design phases but some design activities can in fact be performed during the problem analysis or the definition phase of a project. Even during the realisation or later phases, there may be a need for adjusting or even modifying in depth the design.

The position of the design phase, relative to the other phases, pertains to the chosen methodology for the project. The methodology defines the phases, the milestones, the intermediate checkpoints, the nature of the activities to be carried and the results (deliverables) to be delivered by each phase. Consequently, it is the project methodology that defines the scope and the level of detail of each phase, including the design phase(s).

The initial phase conveniently called definition phase, defines the TO BE situation to be reached at the end of the project. This definition encompasses the elements of the TO BE situation: the future context(s), the agents involved, the artefacts, the relations between people and people, between people and artefacts, and between artefacts. The design phase normally follows the definition phase, whereby the definition of the artefact(s) with the knowledge gathered during the definition phase is used as input. Very often, defining artefacts during the definition phase goes beyond typing the artefact; some properties are already defined and evaluated which is in fact a design activity. During the following design phase, the definition of the artefact may be questioned and modified and hence, provide feedback to the definition phase and possibly to the definition of the TO BE situation.

The project methodology defines also the relation between the design and the realisation[5] phase(s) that may take different forms: a sequence (waterfall), in parallel (with some level of concurrency between design and realisation) or nearly completely in parallel (full concurrency). Similarly, the project methodology may divide design into different phases whereby the scope is different for each of the phases: a phase with full scope (the whole) artefact but with a high level description followed by a phase with the same scope but completely detailed, or first, a phase focused on the core of the artefacts (for example, in a project planning software tools, the planning algorithm) and in a later phase, the data manipulation and management routines).

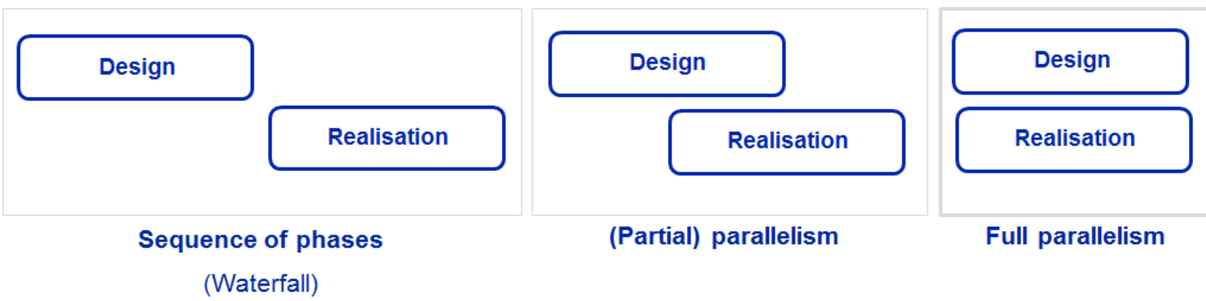

Figure 4: Variants in sequencing design and realisation

Planning concurrency in design and in realisation is used for reducing the total elapsed time of the project. One of the techniques, as illustrated in (Denker, 2001) is to determine the dependencies between artefact aspects and properties. If the interdependencies are not too complex and if, the design subjects can be dealt with in some kind sequence. For complex artefacts however, the iteration will consist of a series of design stages for the complete artefact.

For technical projects the way how design is organised, is determined, among other factors by the aspects of uncertainty (risk). (McLain, 2009) goes further and proposes an approach for quantifying project characteristics related to uncertainty. (Lough, 2009) shows, for a concrete example, how risk can be coped with in early design.

Later phases in the project (after realisation) often provide feedback on the design and depending on the nature and the consequences of the changes to be made, the design phase may have to be restarted, at least in a limited form.

An example of distribution of the design activities over the respective project phases, can be found in (Pons, 2008) p.83. Design is the characterisation of the nature of activities. Design is not necessarily a phase on its own.

[5] Realisation can be partial or tentative in the form of a prototype.

Special situations

- When several artefacts have to be designed in an integrated way such as in system engineering, there will be a design phase dealing with the integrated set of artefacts, design phases dedicated to each of the artefacts (sub-system design) and finally, a phase that integrates the several sub-system designs into a single system design.
- In innovation (or experimentation), there may be a nearly full parallelism between the design phase, the realisation phase and even the (initial) operation phase.

3.3.4.3 The relation between project and design

The project intent forms the basis for the definition of the design activities, in terms of object (one or more artefacts), in terms of activities to be carried out, in terms of results to be achieved. It is the project methodology and more specifically, the overall project planning that determines the scope and the position of the design activities with respect to the other project activities.

As the project is performed by a project organisation, the project determines also the resources that will be made available for design.

These subjects will be examined in more detail in section 3.7 design organisation.

3.3.5 Key statements

Definitions

- A situation consists of actors, objects and interactions between actors, between objects and between actors and objects.
- A project is set of actions that aim at achieving change, by transforming or starting from a given situation into a new (target) situation.
- The project is driven by and implementing an intent by reaching the TO BE situation.
- The intent is held by the sponsor or it is the consolidation of the intents of the stakeholders.
- Most often, a project is carried out in phases. One of these is the design phase. The design phase is the phase encompassing the design activities of the specific project.
- The design phase consists of knowledge construction about the artefact.
- The artefact is a part of the TO BE situation.

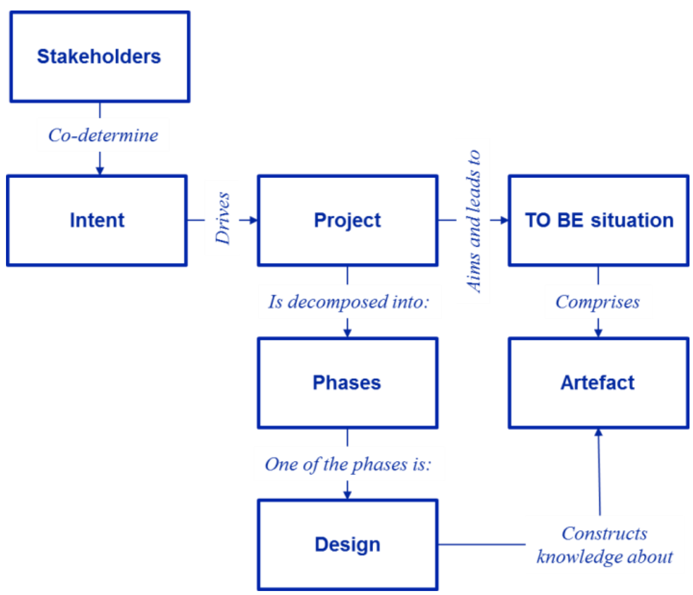

Figure 5:Key concepts of a project

Assumption

- Projects involve uncertainty due to the incomplete knowledge of the starting situation and of the future situation, and due to the limited control over the transformation process i.e. the move from the existing to the TO BE situation.

Statements

1. The project defines the object of design (one or more artefacts).
2. When the action of realisation of the target situation is postponed due to an unacceptable level of

uncertainty, preliminary activities consisting of knowledge construction are developed.

3. Design is one type of preparatory activities aimed at reducing uncertainty by specifying the artefact(s) to be realised. Design is artefact-centred.
4. Design is by essence different from realisation. (Prototyping forms a boundary situation as a prototype could be considered as the expression on some medium of the specification or it could be considered as the beginning of realisation).
5. Design, as a knowledge construction activity, starts on the basis of the knowledge available at that moment and is building up to a point of acceptable uncertainty.
6. The project determines how the design activities are phased over the life-cycle of the project.

3.3.6 Discussion and conclusion

This section is about the role of design in relation to a project i.e. the reduction of the uncertainty as to the project which leads to definition of design as a process of knowledge construction, knowledge being the response to uncertainty. This definition deviates as compared to the definitions that can be found in literature that are often associated with the actual artefact and its impact on users.

Along the same lines, reduction of uncertainty up to an adequate level is a criterion for terminating design which is aligned with the statement of Simon (1972) that design is governed by a satisficing criterion.

As compared to the Status Quaestionis, the proposed contribution elicits the relation between the project and the design activities in terms of inputs from the stakeholders, of requirements and constraints that derive from the context wherein the project is taking place or of additional objectives and constraints that are associated with the planning and the phasing of the project. Indeed tight constraints on schedule or on budgets can have considerable impact on the quality of the design.

3.4 The artefact: different perspectives

3.4.1 Introduction

The artefact is what is being designed; it is the object of design. There are some fundamental questions pertaining to artefacts in the context of design: their nature, their purpose, their properties and also the way knowledge and experience about artefacts is built up by an agent as they form the basis for imagining new artefacts.

The purpose of this section is to provide a series of definitions with respect to artefacts, to illustrate the relation between agents and artefacts on the one hand, between agent cognition and the artefact, on the other. These relations are considered to be the sources of properties of artefacts (as experienced by people). It is quite important to notice that the way people and groups of people experience objects and artefacts depend on their personal knowledge and experience with the artefact and also on the context wherein they interact with the object or artefact. In addition, the notion of properties will be developed.

This section intends to show the relative (subjective) character of (the views on) an artefact by different agents, a factor that has to be taken into account by a designer who is concerned by the different viewpoints of the stakeholders involved. There is also a basic distinction to be made between the 'function' of the artefact as intended by the designer and the function as experienced by another person, given the circumstances of the interaction.

Design is about artefacts; however, a lot of statements about artefacts that are made in this contribution may relate to natural objects as well.

3.4.2 Related work

When examining design literature, as said in previous chapters, a lot of attention has been paid to the design process. In more recent years, attention has partially shifted to cognition and design. However, the subject of the artefact as the object of design is singularly absent but for a few exceptions. (Andreasen, 1998 a) in the domain of design engineering, has stressed the importance of artefact theories for the theory of design. A lot of attention is paid to the development of a design language aimed at articulating the design activity and the artefact to be designed, with focus on the latter. He later proposed a design language for synthesis and systematisation (Andreasen, 1998 b) which is however relating to engineering design as such, which means strongly oriented towards technical artefacts and systems. (Suh, 2001) through the minimum information axiom, proposes a criterion to be applied to the artefact being designed. However, this is a criterion to evaluate the quality of the design; it does not describe the nature of the artefact.

Recent studies have been carried out in the domain of engineering as well as in the domain of philosophy of science, examining the nature of artefact, which goes beyond their technical nature in (Kroes, 2002) and

(Crilly, 2010). An author's citation illustrates the challenge to deal with artefacts in a general way as it is the case for a general theory of design: McLaughlin (2001) (p. 60) " …[t]he function of an artefact is derivative from the purpose of some agent in making or appropriating the object; it is conferred on the object by the desires and beliefs of an agent. No agent, no purpose, no function…". Kroes goes on by stating that : "…Alongside McLaughlin's sweeping statement: …No agent, no purpose, no function' this approach implies 'No material object, no physical capacity, no technical function…". He suggests that there should be more research in the study of technical artefacts, also from philosophers. In fact, these suggestions should be extended to the research in design, also engineering design, especially when engineering extends more and more to the virtual world.

Artefacts once designed and realised, pursue their own life-cycle as they are perceived, interacted with, used by many people, not infrequently in a way that was not planned or envisaged by the designer. Artefacts belong as well to the domain of design and realisation in a particular discipline such as architecture, engineering, crafts, as to the economic and social domain. An extensive analysis of the use and role of artefacts should probably explore and build on contributions coming from economic science, sociology, anthropology and even philosophy.

While trying to understand in depth the nature of design, it is essential to acknowledge that there are commonalities between the design of a building and of real-time software, but there are also differences. Many of these differences depend on the nature of the artefact dealt with. On the other hand, if design is to take into account the needs and wishes of 'users' or 'consumers', the designer has to understand and in many cases, to anticipate the normal use, the exceptional use and the misuse a person may make of a given artefact.

3.4.3 Key concepts

One can find in appendix 6.2 a series of considerations on agents, objects and the cognition of objects as well examples of artefacts. It is background information for the rationale developed below.

Artefacts are created by humans. As a starting point, we refer to a dictionary definition such as the new lexicon Webster's Dictionary of the English language (1990 edition) defining an *object* as: "a perceptible body or thing, a thing or conception towards which the action of the thinking mind, considered as subjects, is oriented".

This definition illustrates some of the characteristics of objects: their perceptibility i.e. the capacity to be perceived by an agent, and the possibility of such an agent to recognise or to imagine an object (the action of the thinking mind). Implicitly, it refers also to an object as being discrete, i.e. in being distinct from another object and from the person who interacts with it by thinking of, by perception of or by action on the object.

3.4.3.1 The concept of artefact

In the present research project, only *artefacts* are considered, in other words, objects that come into being by human intervention[6]. Artefacts are objects that are not originally present in nature. Sometimes natural objects may be used as a tool: it can be a stone used to crush edible plants. The unmodified stone as found somewhere in nature is not an artefact. Artefacts are subject of transformation in the sense that they can be imagined, defined, described, specified and realised. They are deemed to be transformable (changed or created). At the design time, this transformation is in most situations tentative: the process of realisation verifies the feasibility of the transformation.

Not all components of an artefact dealt with in design are themselves artefacts. For instance, in garden design, the artefact is the architecture of the garden (the layout, the combination of elements) while other elements (plants, trees and animals) are natural.

Examples of artefacts are:

- 'Physical' devices: a tool, a car, a module of software code (as programmed), a building, a (intentional) sound;
- Virtual objects: a movie being displayed (the sequences of scenes), a scene generated by computer, software (as executed);
- Social objects: a document, an organisation, money (a bill), symbolic artefacts (ex. a tree transformed in totem), a logo, a state as the organisation of a country;
- Complex and heterogeneous systems (an integrated set of devices and social objects; for example, the American space launch system consisting of the Space Shuttle system with the associated facilities, organisations and people.

According to the above definition, the list of objects and even, types of objects appears ended-less and is conditioned, where artefacts are concerned, by the creativity and the art of those imaging and/or creating them.

The above definition leads to conclusion that the term "object" can be recursively applied in the sense that a part of an object that can be distinguished from other parts is also an object and the combination of several objects that stick together in some way, can also be considered as one object. Hence, the definition of an object is relative: it depends on what under consideration, by somebody, at a given moment. Hence, there is a lot of subjectivity involved.

3.4.3.2 The concept of human-artefact interaction: function and ergonomics

An *agent* is a person who acts. Agents 'learn' of 'know' about objects and artefacts via two channels: the direct interaction with the object and the communication with others, about objects.

During the interaction with the artefact, the agent experiences two set of properties: the first set pertains to the *function* (the role, the utility and the interest for an agent), the second to the *ergonomics* (the way how

[6] We not consider artefacts manipulated, modified or created by animals.

the agent physically interacts with the artefact, given his own physical and cognitive characteristics, and how he experiences the feedback from this interaction).

3.4.4 Rationale

Key aspects in the rationale developed about artefacts are:

- Agent-centred properties which means a series of properties of objects are agent-dependent and moreover, context-dependent.
- Property classes as experienced: this a limited set of property classes that are valid for all types of artefacts,
- The attention to be paid, in design, to the artefact and finally,
- Property classes as designed.

3.4.4.1 Agent-centred and context-centred properties of objects

In most design theories and approaches, properties are considered in an 'objective' perspective, in other words, one tries to identify properties that are, if not measurable, at least perceived in a standard way by many people. From the point of view of the designer, an important design activity is to determine the properties of the future artefact. To ensure that the artefact offers some value to future users, he has to take into account the views of these users and try to determine how they will perceive the artefact and its properties.

For a single agent, the properties of an artefact are to a larger part subjective, especially when the artefacts are imagined, as during design. When different agents are involved and when they reach some level of consensus, the properties of the artefact whereon there is consensus, are defined as inter-subjective. Personal cognition related to artefacts is agent-centred and social cognition (shared by several agents) is group-centred. The perceived properties are also depending on the overall context (technological, economic, social and cultural). For example, a chair first seen by a tribe that is used to sit down on trunks may not necessarily recognise, at first sight, a chair but rather a throne i.e. a sacred object reserved for their king.

Properties of objects and artefacts emerge during the interaction in a given context. Are the properties inherent to the objects or are they only present during the interaction in a given context? This is a philosophical question that goes beyond this study. In design, the question is about specifying the artefact so that the required properties show up when the agent interacts with the artefact in the intended context. The properties as experienced during an interaction may vary and depend on the context.

For example, a car exposed to the sun will feel hot; this is of course not a permanent property. The challenge to the designer is to take into account the diversity of agents concerned and the variability of the contexts wherein an artefact can be interacted with. The challenge involves even a dynamic character: the successive interactions between the agent and the artefact modify each time the cognition of the agent: it is the phenomenon of learning, for instance, about the utility the artefact may have in different situations and about the best way to physically interact with the artefact.

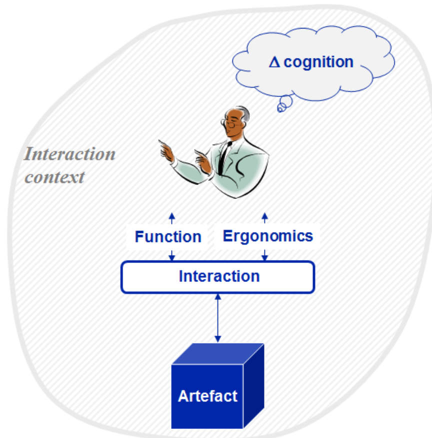

Figure 6: Agent-artefact interaction (one agent)

The above figure shows the interaction between one agent and one artefact, for example, in the case of a tool. The figure below shows the interaction between two people, for example in the case of social networks.

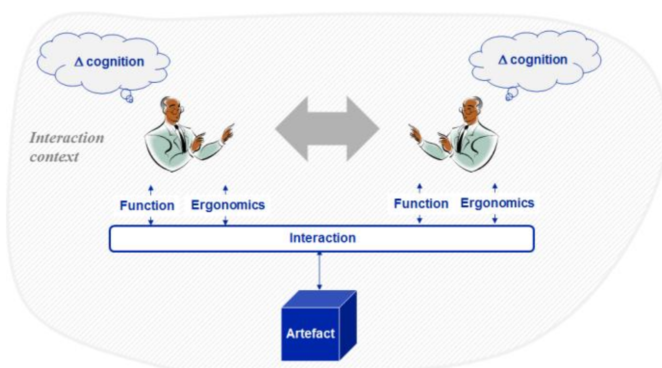

Figure 7: Agent-artefact interaction (two agents)

3.4.4.2 Property classes (as experienced)

In order to remain general, there was no attempt to consolidate property classes that are proposed for engineering design by different authors. What follows is the set of main classes of properties deemed to be applicable to a wide range of artefacts, across design domains. There is also a level of subjective evaluation by the designer: depending on the artefact he is designing he will elicit those properties that he considers the most important.

The properties that are detailed here are the properties as experienced by agents (users, operators, etc…), not the properties as allocated by the designer to the artefact in the course of the design process.

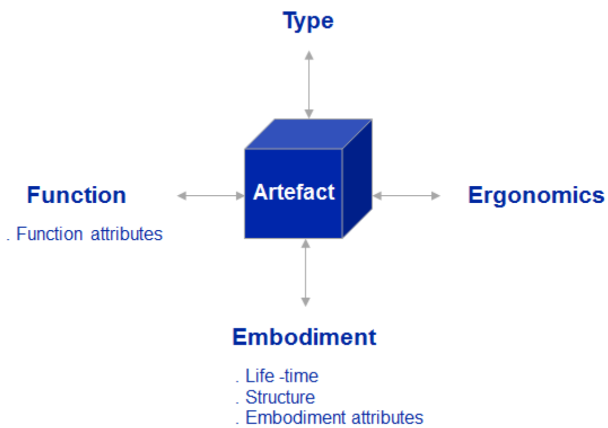

Figure 8: Property classes of artefacts

Type

The type of artefact: the type is a categorisation or typology established by the agent or an external typology that is referred to. In other words, he is not always referring to formal classifications. Each person is deemed to build his own categories. People sharing the same environment and culture will tend up to a certain point to align their classifications. However, minor or major differences may remain leading to arguments but also to the enrichment of the perspectives on a given artefact. Classifications may change over time.

Type is interesting for communication about the artefact. Type is also useful in referring to the properties of existing artefacts of the same type.

Function

The term 'function' is the function *as experienced* by the agent: it is agent-dependent and context-dependent.

Artefacts are designed and realised with some intent in mind. Sponsors, stakeholder and designers may have all different intents and hence, their expectations as to the future artefact may all differ. They may want to build, to use, to sell, to own or to show the artefact. The synthesis of or compromise between different expectations is the function of the artefact *as designed*. Function, as defined in the context of this research, goes beyond the technical function of the artefact. Certain objects are not 'used', for instance, in the case of symbolic objects. What is the technical function of the Eiffel Tower? It may be that the intended utility is no more applicable, for instance, as a technology demonstrator and that is replaced by the role of Eiffel Tower as a landmark.

Therefore, we will use the 'function' of the artefact in a general way and whereby the function-as-experienced is dependent on the agent, on the interaction the agent has with the artefact and on the overall context. Function is the importance (the relevance) an artefact has for an agent in a given situation.

A simple example of agent and context-dependency of function is the situation where the agent wants to assemble something using screws and where the only tool he has is a hammer. Clearly, the notion function-as-experienced differs from the intention laid down in the hammer.

To specify further the notion of function we propose it to be defined according to three dimensions[7]: (1) the function of the artefact for the person himself, for its identity and self-image, (2) its function for the interaction with others through communication, collaboration, group creation and behaviour, social and cultural aspects etc., and (3) its function for the interaction with nature (the physical environment). These function dimensions are called: (1) identity-related, (2) relational and (3) technical.

This three-dimensional approach to function concurs up to a certain level with the contextual character of function and use as expressed by (Scheele, 2005) who argues that: "…notion of artefact functions is constituted, not only by the more traditional elements of a physical structure and the causal or intentional history, but also by the social context in which the artefact normally is used". He has distinguishes the notion of proper function and the accidental function use. This is a designer-oriented perspective.

Function dimensions	Aspect	Example (impact of an artefact)
Identity-related function	• The world vision of the specific individual	• The picture of the full earth by Apollo 8.
	• Self-image	• The self-image associated with mastering a new tool.
	• Internal states (affects)	• Self-confidence associated with owning an artefact. The pleasure to play with a toy. • The relaxation after playing

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[7] The notion of function and function dimensions has been the subject of investigation over a very long time and the tentative definitions have evolved accordingly. In the end, it came to question the role of an artefact in addressing and solving, at least partially, key problems in one's life. It ended by stabilising into a three-dimensional notion of function. It has to be noticed that in the literature investigated, one could now sense some initiatives to take into account the social aspects of artefact but no comprehensive model was found. Strangely, the three-dimensional notion of function concurs with a statement in the novel of Somerset Maughan, Of human bondage (1915), p. 226 (Edition in the public domain: Project Gutenberg) where the main character comes to the conclusion that the three main problems that a human being is facing in life, are (a) the relation to one-self, (b) the relation to nature and (c) the relation to the other.

Relational function	• Changing the (power) position within a group or organisation	• A throne • The category of company car • (The ownership of) a weapon
	• Communication & collaboration	• A telephone • An e-mail message • A computer network
Technical function	• The capacity to change the physical world	• Compensation of missing capacity (a prosthesis) • Performance improvement: enhancement of available capacity (a hammer) • New capacity (an airplane as opposed to a ship)

Table 2 : Dimensions of function

Artefacts may have a function according all three of the dimensions, their relative weight (importance) ranging from low to high. Depending on the domain, and on the particular artefact that is being designed, function might be considered in levels of detail, for example,

- At level 1: the main function dimensions e.g. for a car, the pleasure of driving, the safety, the prestige associated with a car, the overall technical characteristics, …
- At level 2: the identification of the factors that are influenced by the artefact and that contribute to the importance of function in the different dimensions e.g. for a car, the comfort, the aesthetics, the rare colour, the aesthetics, the performance, … all characteristics that are important in driving, showing, possessing the car).
- At level 3: the properties of the artefact that ensure that these factors are influenced as intended e.g. for a car, speed, power, weight, autonomy, …)

It is most probable that these levels are not always applicable and therefore, they are given as examples.

The function in each of the three dimensions may evolve over the life-time. It is conditioned by the stability of the artefact over time. Obviously, a bridge, if it collapses, cannot any more be a tool for crossing a river and nor act as a symbol.

The three dimensional approach to function is quite in line with the position taken by (Crilly, 2010) about the roles that artefact play: technical, social and aesthetic. In the present proposal the aesthetic role is expanded to an identity-related role.

Although emotions are not taken into account in the present study, it is interesting to note that emotional binding with the artefact, which is by nature agent-centred, is considered valuable to be studied (Mugge, 2009). A similar remark can be made about the novel character of a product to an agent (Mugge, 2012): novel products are more appreciated than older ones.

Emotional binding is not limited to users and operators (for example, the feeling of a ‘loss’ among the operators team, when the Galileo probe entered and burned up in the atmosphere of Jupiter at the end of its life) and is most probably applicable to the designer as well.

Ergonomics

These properties pertain to the ‘look and feel’ of an artefact and more generally as to how the artefact is perceived through the five senses, as to the ease of interaction and the level of control that one has on the object (the predictability of its behaviour). Some of these properties are subjective properties as for example, a given artefact can feel relatively light to a strong individual and heavy to a weaker one. Other cases, with relatively autonomous artefacts (a robot, a power plant or an airplane) it will depend also on the internal control mechanisms within the artefact, mechanisms that may be known or not by the user.

Embodiment

An artefact, in order to go beyond the state of a concept (that can be talked about), has to be embodied. Embodiment properties pertain to the materiality of the artefact: stable materiality for ‘real’ artefacts and the transitory materiality for virtual object, for example, projection of slides or execution of a program.

For virtual objects, the embodiment deals specifically with the implementation of the artefact by the resource and with the capabilities of the resources to do this.

Closely associated with the embodiment properties, is the life-time property. It is the time an artefact has to or expected to last, introduces a time dimension in the properties of artefacts. It is the qualification of the expected or experience life-time and pertains, among other, to the structural stability over time of the artefact as well as to the possibly different embodiments over time.

Examples

An example of difference in function that is person-dependent and context-dependent is the following. The statue of a saint may have a high symbolic value for one person. For another one, he can use the same statue as a paper weight.

The scale model of an airplane can act for an aeronautical engineer, as an ornament but when designing, he may get inspiration when handling and moving the model and by looking at it from different perspectives. This means that the function as allocated by a designer (function-as-designed) is not necessarily perceived as function by the users (function-as-experienced).

3.4.4.3 The importance of artefact properties for design

Artefacts are ‘personalised’ through the individual cognition that people develop about them. There is a lot of artefact cognition that goes beyond the ‘objective’ (in fact, inter-subjective) knowledge pertaining to what is perceived as reality. In design for different stakeholders, there is a need to de-centre the analysis of the needs and to identify the expected use and more generally speaking, the function for the different stakeholders. In this respect, typing an object (as seen by the different stakeholders) is important as it is the starting point for activating cognition pertaining to the typologies that the stakeholders have developed about artefact. The same applies to the actions that stakeholders have performed with existing objects and that they expect to perform with and on the new object.

An illustration is of this is provided in (Law, 2002) where the development and the airplane itself have several meanings to the various groups of stakeholders (manufacturers, Ministry of Defence, pilots, maintenance crews, mission planners, strategists, Ministry of Industry, etc…), leading to a considerable diversity of needs expressed by them. The consequence is that, when taking into account all these requirements, the project becomes more and more unfeasible, at least when there are budget constraints.

The agent-centred approach to artefacts concurs with (Brown, 2010) who argues that designing for human extension rather than human substitution: “Design is about service on behalf of the other meaning that the designer practices the design process on behalf of the user in order to bring about purposeful change and meaning … in order to solve the ‘wicked’ design problems designers face… designers need to move beyond user participation and provide designs which develop users’ abilities, freeing them to help the designer more effectively help them”.

3.4.4.4 Properties as designed

Properties as designed will be addressed in the section on the design space and on the design process. What can already be said is that properties as designed belong to the same main categories. However, when the designer is at work, he deals with the function-as-designed. The same applies to the intended ergonomics.

3.4.5 Key statements

Definitions

- An artefact is an object that is created by human intervention.
- An interaction with an artefact may consist of perception through the five senses, action with or action on the artefact.
- The function of an artefact is the role that an artefact plays or the utility that it presents to an agent.
- The ergonomics is the way how an agent interacts physically with an artefact and the associated comfort of discomfort.

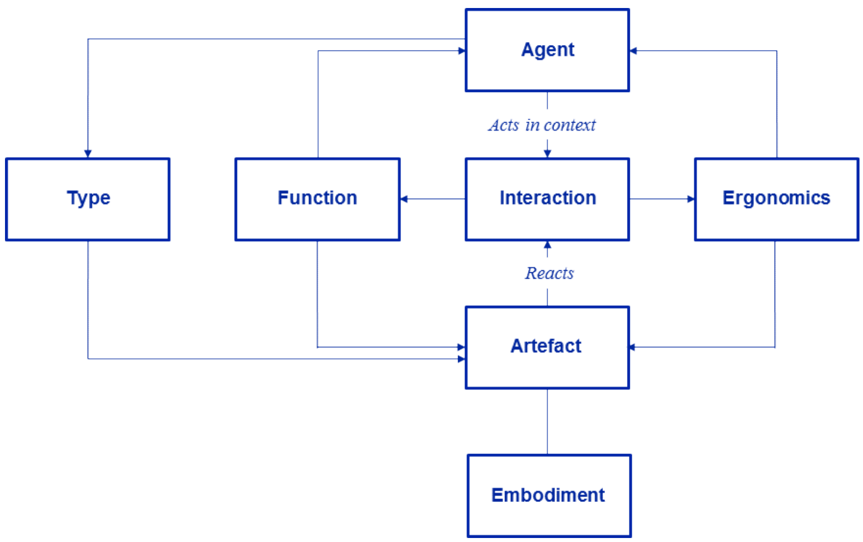

Figure 9: Key concepts for the artefact as experienced

Assumption

- An agent knows objects through the cognition he builds up by interacting (including perception) with the object and by communicating about the object.

Statements

1. The cognition (the knowledge and experience) of an agent about an artefact changes at each interaction.
2. The cognition that an agent builds up during the interaction integrates on the function and the ergonomics of the artefact during that interaction and depends on the nature of the interaction and the context wherein the interaction takes place.
3. The interactions that an agent may have with an artefact depend on the type of artefact (technical artefacts, symbolic artefacts, virtual artefacts, combined artefacts).
4. In the context of design, two perspectives on properties can be adopted: agent-centred (properties as

perceived) and properties allocated to the (future) artefact during design (properties as designed).

5. These properties pertain to the property classes: type, function, ergonomics and embodiment.
6. Function is three-dimensional: (1) identity-related, (2), relational and (3) technical.
7. Properties as defined by the designer pertain to the same classes. They are allocated on the basis of the intent of the designer.

3.4.6 Examples

The properties of a car

The artefact ‘car’ provides an excellent example. Its technical function is determined by its capability to drive with a given speed, over a certain distance and with a high level of safety. It is sometimes called ‘primary function’ but this qualification is not always shared by the clients who may consider their car as a status symbol or a means to transport goods rather than people.

A car may also be relevant in the relations with others, for, depending on the model, increasing the prestige of a person or to the contrary, for expressing modesty. Finally, a given model of car may enhance the self-image of the person, because he has a new toy to play with or because he appreciates the fact that he proves his capability to drive such a car.

The life-cycle of the car can be looked at: from a technical point of view (Is the car capable to provide the physical capability over a long period of time?), from an economic and social point of view (For instance, does it still contribute the image of the person?) and from an identity point of view (Is it still contributing the self-image of the person?).

The properties of a watch

The technical function of a watch is to give the exact time. An expensive watch can an expression of wealth, in social interactions. A complicated watch can be played with by using all the capabilities of the watch (chronometer, count-down, the position of the moon, …)

The properties of a planetary probe

A planetary probe has a technical dimension: to act as a vehicle for a set of instruments for performing planetary exploration. In a space race it is also an indicator of technological prowess of the country that launched it. When successful, it is a source of profound satisfaction for proving to oneself that it could be built.

3.4.7 Discussion and conclusion

This section illustrates the need for a designer designing for different stakeholders, to be aware of the function the artefact may have for them, taking into account the personal differences, the possible context of interaction and the type of interaction.

3.5 The design space: structuring design knowledge

3.5.1 Introduction

The notion of design space is the subject of this section. In the contribution on the project as context for design, design has been defined as knowledge construction. The concept of design space is to explain the knowledge content to be elicited and constructed during the design process: it focuses on the 'What' while the next contribution on the design process is focused on the 'How'. Both contributions are complementary.

One of the key concepts is the concept of design space. It is the virtual space where the design knowledge is built up. The concept as used in this contribution has probably been influence by design literature but the main reason to adopt it was to cope with all kinds of design processes ranging from very methodical to quite chaotic, able to reach, in principle, the same result. The different approaches may lead to differences in design performance (for example, the time required for reaching an adequate design) but in the present study, the subject of design performance is not addressed.

A way to cope with these different approaches was to consider the content of the knowledge as of primary importance and not the way to get there. The notion of the design space where all knowledge is built-up becomes then a unifying element as being the space where a design process acts on.

3.5.2 Related work

Many authors involved in design research use the notion of design space or spaces. However, there are differences in content. (Goel, 1992) deals with the notion of design problem space.

Lossack (2002) and Grabowski (1995) use the term of design working space based on a system theory approach. The design space may be partitioned in sub-spaces and the design space is conceived as being layered, each layer containing elements such as product requirements, functions, physical principles, etc. The design working space contains the description of the system being designed and apparently, other information such as requirements and working principles.

Tomiyama (1998) uses the notions of function space and attribute space and design involves a process of mapping functions and attributes. He adds a third space called the meta-model space acting as a reference for generating candidate solutions.

Suh (2001) focuses on the notion of the 'design world' and four domains: the customer domain, the functional domain, the physical domain and the process domain (processes that generate the design parameters proper to the physical domain).

Hatchuel (2008) has still another approach. The C-K theory refers to two distinct spaces: the Knowledge space and the Concept space based on the idea that knowledge is a proposition with a logical status for the designer or the person the knowledge is aimed at while a concept is a proposition without logical status. On and between the C and K spaces, a limited set of operators are used for describing the design process.

There appears to be a common ground to the above perspectives of the design space. It is a virtual space populated with design knowledge and the authors differ in the scope of content of the design space. Hatchuel stands out in defining logical operators establishing relations between the concept space and the knowledge space and acting on these spaces.

The following table provides an overview of the different concepts of design space:

Author	Design space structure	Contents
Goel	One space	• Problem space
Grabowski & Lossack	Multi-layered space	• Layers may be defined at will • The (primary) layer contains the artefact description and its interfaces to the outside world
Hatchuel	2 spaces	• Knowledge space • Concept space
Suh	1 design world subdivided into four domains	• Customer domain • Functional domain • Physical domain • Process domain
Yoshikawa/Tomiyama	3 sub-spaces	• Function sub-space • Attribute sub-space • Meta-model sub-space
This thesis	Design space that can be subdivided in areas and layers at will	• See below: the nominal target content of the design space

Table 3 : Comparison of design space related concepts in design literature

3.5.3 Key concepts

The *design space* is hereby defined as the virtual space where design knowledge is built up. It contains all the knowledge elicited and built-up during the design process. The design space is the space whereon the design process acts. The state of the design space, more precisely, its content evolves continuously during the execution of the design process.

It has be noticed that design space stands for all the design knowledge that is elicited[8] during a given design project.

The concept is close to the working memory of an individual in cognitive science or, physically, the blackboard or flip-chart i.e. representation tools shared by a group of people. Some authors include also

[8] Elicited means that is conscious of the designer(s) involved. It is not necessarily expressed on some medium as design documentation.

(design) process elements in content of the design space which is not the case with the proposed definition. For this theory, the goal is to describe design whether the design process is managed or not.

A benefit associated with this concept is that it provides a ‘topological’ view of the different elements of design knowledge instead of or as a complement to a process view. With the notion of design space, the design process becomes a process of enriching the design space up to a situation whereby the level of completeness and the level of consistency between the respective content elements are considered acceptable by the designer. This evaluation is not simply arbitrary or merely subjective: the designer may use external standards and norms or inputs from other people so as to verify the adequacy of the design.

3.5.4 Rationale

The rationale about the design space deals with:

- The nominal content of the design space
- The type of contents (knowledge) in the design space
- Variations as compared to the nominal content
- The level of detail and consistency (of the contents) of the design space, and finally,
- The indication of possible instances of the design space.

3.5.4.1 Design space and areas

The design space can be decomposed in *areas* that may become themselves the centre of attention. Hence, depending on the capabilities of the system (designer, team, tool) that instantiates the design space, the design space may be unique or a collection of interlinked sub-spaces, such like a computer windowing system.

The design space can be mono-layered with different areas where knowledge is being built-up but it can also be multi-layered. As long as the design space is not implemented on some kind of medium, this makes no difference and at conceptual level a single design space will be used.

<u>The nominal target content of the design space</u>

In order to define more precisely the target content of the design space, one has to go back to the purpose of design, namely, to build-up knowledge about the artefact so as to reduce uncertainty to an acceptable level. The content of the design space is pertaining to different areas (the equivalent of sub-spaces and layers according to Grabowski).

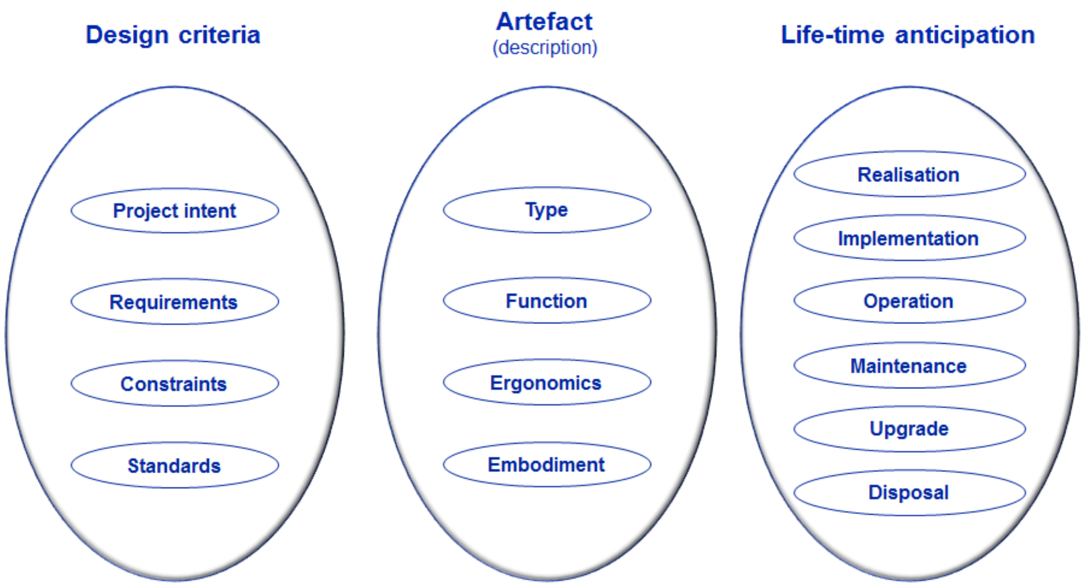

Figure 10: The nominal content of the design space

Note

The relationships between the (content of the) areas of the design space are not shown. In fact is up to the designer(s) to identify these and when needed, to make them explicit.

Design space area: artefact

It is obvious that knowledge has to be built up about the artefact and its characteristics:

- The *type*: definition of the (future) artefact in reference to some typology. It may be used for communication purposes but it may also be a source of inspiration for identifying the properties of artefacts of the same type.
- The *function*: function-as-designed is deemed to have the same dimensions as the function-as-experienced: identity-related, relational and technical. It is the intended function the artefact will be supposed to have for different users and other stakeholders in different contexts. Function-as-experienced, described in the section on artefacts, is pertaining to the agent's experience of the artefact in the possible contexts of interaction which may differ from agent to agent and context to context. Function may be further decomposed in more detailed functional properties, static and dynamic, i.e. the main characteristics of the artefact that will provide the intended function.
- Ergonomics: the type of users and operators that is targeted at with reference to their physical characteristics and their physical and cognitive capabilities. Ergonomics may be further decomposed in more detailed ergonomic properties i.e. the relevant properties the artefact should have for the targeted users and operators, in so far they are explicitly defined.
- The artefact embodiment; the definition of the type of embodiment (Is it a physical or a virtual product and which one?): life-time, structure and the physical properties of the artefact and its components

Aspects to consider for the specification of the artefact are dependent on the type of artefact and probably more structured in engineering and architecture than in other design domains. (Gero, 2002) has the FBS (Function, Behaviour and Structure model). (Hubka, 1988) uses three categories: design properties (e.g. function, form, tolerance, surface, materials and dimensions), internal properties (e.g. strength, stiffness, hardness, elasticity, corrosion, resistance, etc.), and external properties (e.g. ergonomic, aesthetic, economy of operation, reliability, maintainability, and safety). The ISO 9000 (2000) standard defines also categories of properties. (Sy, 2011) in a perspective of product design based on life-cycle features has following categories: attributes, topology, geometry and relationship (with other elements and artefacts). The distinction between topology and geometry is interesting because the notion of structure used for instance, by Gero, may lead to different interpretations. Is structure the structure as intended by the designer or as perceived by the user? In fact, the term 'structure' is ambiguous. The design may organise the artefact according to a structure that the user does not see.

Design space area: design criteria

Under this heading are regrouped all the elements that are used in assessing that the artefact is the 'right' one. Authors, who follow the problem solving approach, talk about the problem space as opposed to the solution space (that corresponds to the artefact area). In fact, the *project intent*, the *requirements* that may be collected from future and potential imagined users in innovative design, as well as the *constraints* and *standard and norms* to be applied, constitute together the set of design criteria by which the designer will assess the designed artefact. All these elements may be derived from the analysis of a 'problem' associated with the AS IS situation. In order to maintain the generality of the approach we do not refer to 'the' problem to be solved.

In the section on the artefact, the experience an agent has is double: the function and the ergonomics of the artefact. Two types of requirements can normally be derived from these functional (in the extended meaning) requirements and ergonomic requirements which will to be matched with the properties of the imagined/invented artefact.

Requirements are derived from expectations and needs of the different types of stakeholders. Requirements result from elicitation, consolidation and decision as to the importance and the priorities of the different requirements:

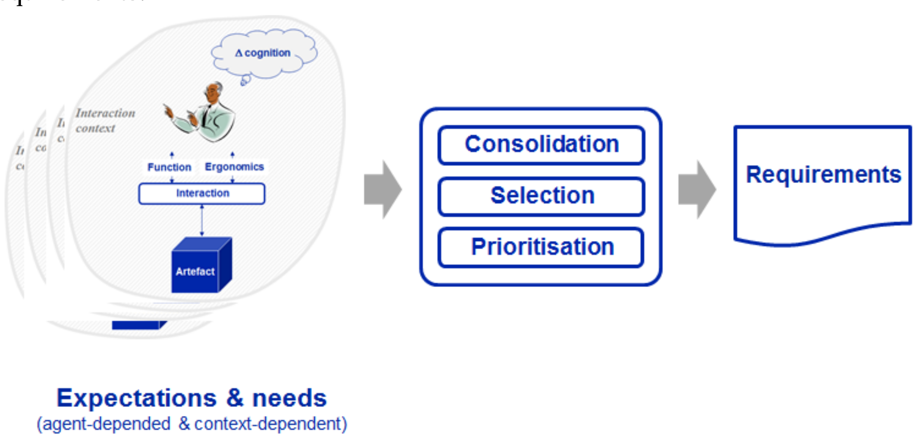

Figure 11: Requirements definition

Design space area: life-time anticipation

Design, being defined as knowledge construction for reducing the uncertainty on the later phases in the life-time of the artefact, should anticipate on these phases. Depending on the level of detail, this anticipation can involve the simulation of the behaviour of the artefact in different contexts or deal with the actual planning of how to realise the artefact.

This design space area comprises knowledge pertaining to:

- The anticipation of the *realisation* of the artefact where attention is paid to the realisation processes to be performed, to the tools to be used, to the available resources or to the resources to be acquired and to the planning and scheduling of the activities to be performed by these resources, and,
- The anticipation of the *later steps* (after realisation until disposal) in the life-time of the artefact. Anticipation means examining the normal (intended) and exceptional situations where a person or a group may interact with the artefact and the consequences of the existence, the operation, the use, the maintenance, the upgrade and the disposal of the artefact may have. It is here, for instance, that ecological considerations intervene in the design process.

<u>The type of contents of the design space</u>

It is important to notice that the contents in the design space are of all kinds of knowledge and not simply words in a given language: it may consist of memories of past artefacts experienced through the five senses, more abstract constructions like typologies, self-developed models, elements of reference models, principles etc. This is determined by the properties and capabilities of the knowledge system that handles the design space. Contrary to the C-K theory (Hatchuel, 2008) there is no distinction between concepts and knowledge.

<u>Variations as compared to the nominal content</u>

The above list of categories of knowledge in the design space is a *nominal* list as defined by the theory. It it's the expression of the full scope of design. In practice, there may be variations between design situations whereby the designer or the design team decide not to consider some categories or sub-categories or on the contrary, expand some categories.

Here are some examples of design situations where the target content of the design space deviates from the nominal content:

- In preliminary design, the designer may give no consideration at all to the realisation and the further life-time of the artefact and will restrict himself to the specification of a feasible artefact.
- In pure innovative design it may not be possible to define requirements nor constraints before describing and specifying the artefact.
- The design space becomes more detailed when a designer investigates in parallel different alternatives for the artefact: the category 'artefact' is then detailed in a many sub-categories, one per alternative and the necessary areas are added in the design space.

- In railway construction when a new railroad has to be added to existing lines, a considerable design effort goes to the ‘phasing’ of the design as the realisation for the reason that the disturbance to the traffic has to be limited to a minimum while progressively building and commissioning parts of the new railroad. The phasing conditions the feasibility of the project and interferes with the design.

The level of detail and consistency of the design space

As said, the level of detail of knowledge and consistency in the design space depend on the designer or the design team and how they evaluate this content in relation to the level of the remaining uncertainty.

There might be two interpretations of the content of the design space: the first states that the design space contains the design knowledge at a given moment; the extended interpretation states that it contains also the history of the design space i.e. all its successive configurations at all intermediate stages. The extended interpretation would be relevant for creating design tools that are able to record all the transitions between states of a particular knowledge element as well as the transitions between different types of element in order to track an actual design process in the perspective of learning.

Instances of the design space

Common instances of the design space are: the mind of the designer (his short term memory), a black-board, or the knowledge-base of a computer aided design software.

3.5.5 Key statements

Definitions

- The design space is defined as the virtual space where design knowledge is elicited and built up. It contains all the knowledge elicited and built-up during the design process. The design space is the space whereon the design process acts.
- The nominal content of the design space is sub-divided in areas with relevant knowledge about the artefact.

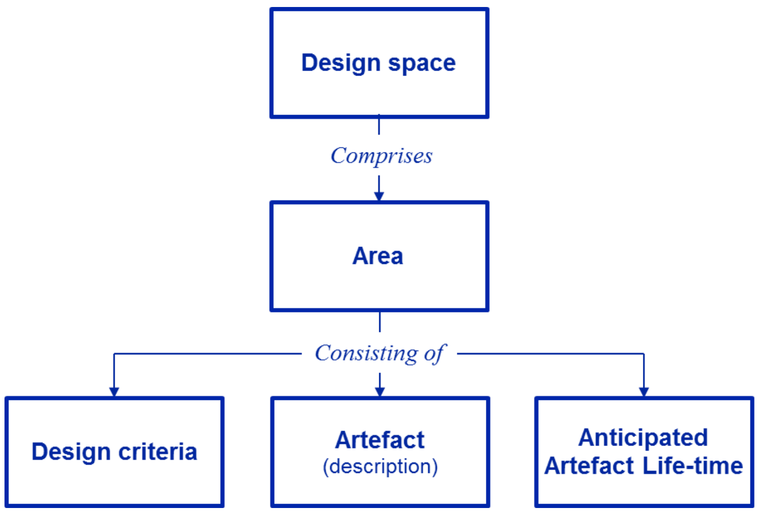

Figure 12: Key concepts of the design space

Statements

1. The nominal target context of the design space consists of three areas.
2. The area *design criteria* is the area where the knowledge pertaining to the project intent, the requirements, the constraints and the applicable norms and standards is built up.
3. The area *artefact* is the area where the knowledge pertaining to function, functional properties, the ergonomic properties, the embodiment structure and the physical properties, is built up.
4. The area *life-time anticipation* is the area where the knowledge associated with the anticipation of the realisation and further stages in the life-time of the artefact until its disposal is built up.
5. The actual scope in terms of area and sub-areas, and content of the design space depends on the scope of design for a given project and on the level of elicitation of the different knowledge elements.

3.5.6 Examples

The memory of the designer

The short term memory of the designer is an implementation (instantiation) of the design space. If the designer works alone, all the design knowledge that is built up in real-time resides in the short term memory and part of it is consolidated in the long term memory. Hence, the short term and the long term memory of the design is the design space for that particular project.

A flip chart for a design team

In the case of a design team, the design space is partitioned over the memory of the individual team members and for example, the sheets of paper of a flip chart that are suspended on the wall of the meeting rooms in order to act as the shared memory.

WWII Peenemünde V-2 design and development

It is interesting to recall that, during WWII, when German engineers were developing the A4/V-2 missile in Peenemünde, there were a series of photographers assigned to take nearly continuously pictures of the content of the blackboard. It is an illustration of early knowledge management (or at least, recording) and it illustrates too, the notion of design space materialised by black boards.

3.5.7 Discussion and conclusion

The notion of design space appears to a largely accepted concept by designer researchers albeit in slightly different forms. Some authors decompose the design space in sub-spaces or in layers; this is not essential at the conceptual level, the most important is the target content.

In this thesis, the proposed design space is characterised by:

- One space with several areas
- Its nominal target content i.e. the areas that have to be completed for fulfilling the purpose of design
- The fact that the design space contains the knowledge that is elicited (depending on the particular design situation and the decision of the designer(s))
- The types of knowledge: all kinds, representations (images of artefacts), texts, concepts that are language related, symbols (for example, the image of a mother with a child to represent the notion of care, …)

Note

In this thesis, the aspect of internal elicitation (manipulating knowledge in a conscious way) and the expression of knowledge (externalisation on some kind of media) are considered to be distinct.

3.6 The design process: design knowledge construction

3.6.1 Introduction

This section focuses on the design process i.e. the generic model of activities to be carried out so as to serve the purpose of design. It is an abstract model: it does not refer to practical instances of design or to the resources involved. This section is complementary to the one on the design space: both contributions are dual descriptions of design, the one by the content, the other by the (generic) activities.

3.6.2 Related work

Design literature offers plenty of references dealing in one way or another with the design process. One can distinguish different approaches or sources of inspiration:

- *Problem solving approaches*: in broad lines (there are variations on the theme) the design process consists of: problem identification, problem analysis, alternative generation and selection (Pahl, 1984) and (Lossack, 2002). This approach finds its foundation in the successive versions of the Science of the Artificial (Simon, 1969 and later editions). Variations exist with (Altschuller, 1988) stating that an abstraction activity is needed so as to come to an abstract and more general problem statement to be solved; this solution is then to be made specific for the particular case. (Yoshikawa, 1998) focuses on the mapping between requirements and the properties inherent to the artefact being designed.
- *The FBS paradigm*: (Gero, 2002) developed the FBS (function, behaviour and structure) model from which the design activities are derived. The design process consists of transitions between F, B and S. More refined variants are emerging (Gu, 2012). The approach strongly focuses on functional knowledge management for the conceptual design. An additional concept 'cell' is introduced in order to more easily deal with knowledge built-in in previous designs.
- *A set of abstract operators relating to set theory*. Although the C-K theory of (Hatchuel, 2002 & 2008) 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. A concept is a proposition without any logical status (true or untrue) while knowledge is a proposition with a logical status. The theory defines four operators (a) that establish a disjunction between knowledge and a concept, (b) that expand the concept space, (c) that expand the knowledge space and (d) that establish a conjunction between concepts 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.

In the perspective of describing design in the most general way, the above approaches suffer from the fact that (a) they are or tend to be prescriptive (they describe what the design process should be) and not what is it is or might be, (b) they appear too rational: they do not take into account that design is often chaotic, at least partially, and (c) they do not take into account the variations in explicitness of the design knowledge. Explicit is defined in relation to the designer(s): single designers may not consider some aspects and rather rely on intuition and a team of designers, especially those working together for a longer period, may make a lot of implicit assumptions or decisions.

3.6.3 Key concepts

When addressing the notion of design process it is necessary to differentiate it as compared to other notions that are frequently used:

A design *phase* is a consistent set of activities in a project, defined by a starting point and the end point, that is principally dedicated to design but that may include other activities such as planning, budgeting and project justification (at that point in project). A design phase can be considered as a sub-project.

The design *process* is the abstract model of the consistent set of activities to be carried out to fulfil the purpose of design namely to construct knowledge about the artefact and to ascertain that it will contribute to achieving the project objectives. The model is abstract in the sense that no reference is made to the resources involved for carrying out the design process.

For completeness, a design *task* is a task allocated to one or more individuals. The design task is a complete or partial instance or in terms of a part of the artefact that is dealt with. This will be examined in more detail in the next section.

3.6.4 Rationale

The rationale about the design process addresses following subjects:

- The nature of the design process
- The structure of the design process
- The evolution of the design space
- The design inputs
- The design outputs and,
- Design strategies.

3.6.4.1 The nature of the design process

As already mentioned the essence of the design process is to build on the knowledge available at the start and to enrich it up to a satisfying level of completeness and consistency, assessed against the acceptable level of uncertainty that remains at the end of the design process.

In reference to the areas of the design space to be enriched, one may distinguish three parts so the target content that has to be generated:

- *Identifying the design criteria*. In most cases, among the foremost design criteria are the project intent and the expected or required function of the artefact to the stakeholders. The latter is commonly called requirements gathering, elicitation and consolidation, or problem analysis leading to this elicitation.

One has to notice that a project is not always started as a problem to be solved ('a man on the moon before this decade is out') and therefore we do not call this problem analysis.

- *Refining the definition and describing the artefact* for evaluation and if positive, for realisation. In a problem solving perspective, this is called: problem solution.
- *Anticipating the artefacts life-cycle*: its realisation in terms of processes and resources as well as the existence of the artefact, its use (proper, accidental or even misuse), its maintenance and ultimately, its disposal. Anticipating may include the identification of potential mitigation initiatives. For technical artefacts, the anticipation may be relating to costs, ecological impact but also aspects such as re-embodiment of parts of the artefact when new materials and technologies become available (for example, for military aeroplanes, a mid-life upgrade).

These processes are to be performed in as much the corresponding area the design space is meant to be explicit and detailed.

With the notion of design space, the definition of design process can be further refined: it is a process of enriching the respective areas of the design space and ensuring that each of the areas as well as of the overall design space is sufficiently complete and consistent.

It should be noted that the design process does not start from scratch: inputs may come from previous phases and projects and from the designer(s) themselves, may hold a lot of knowledge that is immediately available (for example, by re-using a part of a previous design). In many cases, during and at the end of the process, outputs are generated for memorisation, communication and collaboration. Hence, the design process can be considered as an input-output process with a working space (the design space) that is representative of all the design knowledge at a given moment.

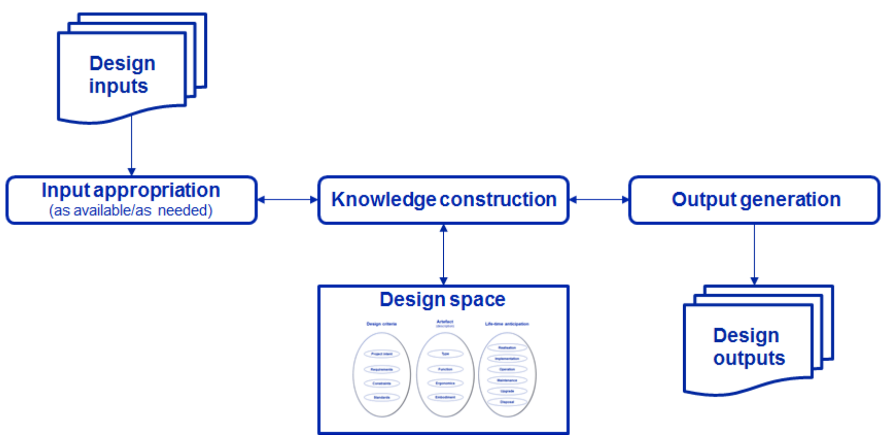

Figure 13: The design process as an input-output process

3.6.4.2 The structure of the design process

<u>Dealing with the areas of the design space</u>

Unless a method is followed by the designer(s), there is no a priori pre-determined sequence inherent to the design process, in terms of areas of the design space to be dealt with. Indeed, as long as the process achieves the goals of a sufficiently complete and consistent design space, there is in principle no precedence of one step over another.

When the type of artefact is relatively well known, it can be recommended to start first with the needs and requirements identification so as to reduce the range of artefacts alternatives. In innovative design, once the general type of artefact is identified, the focus may be on the artefact properties and its embodiment and the verification of the requirements may come later. When the artefact itself is known, for instance, a railway track, the focus can be on the embodiment and the realisation of the artefact. It shows that the sequence of steps is dependent upon the pre-existing knowledge at the start of the design process.

There are nevertheless dependencies that help in structuring the design process:

- *Logical dependencies between areas of the design space*. Design criteria have to be known so as to be able to evaluate the content of the other areas of the design space: they are used for evaluation of the compliance of the contents of the artefact area with these criteria and they can help in reducing the number of alternative artefacts to be examined. In addition, knowledge about the artefact has to be available so as to be able to anticipate its realisation process, methods, tools and resources. A similar statement is valid for anticipating of the artefact life-time.

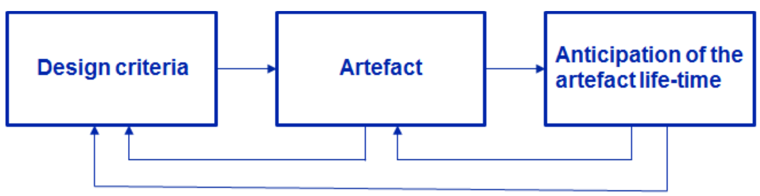

Figure 14: Feed-forward and feed-back between design space areas

  These dependencies do not necessarily imply that the process has to be completely aligned with them. Indeed, formulating hypotheses for one of these areas is equivalent to enriching the design space with tentative content which has to be verified afterwards. For example, one can formulate hypothetical user requirements with respect to the artefact and generate corresponding content about the artefact. In a later stage, these hypothetical requirements can be verified at the occasion of client interviews or even later, when a mock-up or an early prototype has been developed. Another approach would be to invent an artefact and to try to imagine which function this artefact would have for which agent in which situation.

- Dependencies depending on the *nature of the artefact*. For example, for an aeroplane, one might identify key elements of the design such as structural weight, wing area, motor power, fuel quantity and range as well as the relations from one element to another so as to determine a sequence of problem to be addressed.
- The *process approach*: trying design in a series of sequential steps or proceeding by iteration.

Initialisation

The design process starts with the initialisation of the design space in terms of target content: it is the nominal content as defined in the section: Design space. Variation as to this target content may occur depending on the specific targets that have been formulated to a given design phase (as determined by the project methodology).

Sub-processes

Exploring further the design process as a knowledge construction process, as inputs have to be appropriated, they are stored in some kind of memory and to be used as such or after decomposition and re-composition. The memory is in fact a buffer that is situated between input and knowledge processing.
Inputs can be given (for instance, the results of previous project activities) and they can be searched for, whenever the contents of the memory is not sufficient for feeding the knowledge construction process.

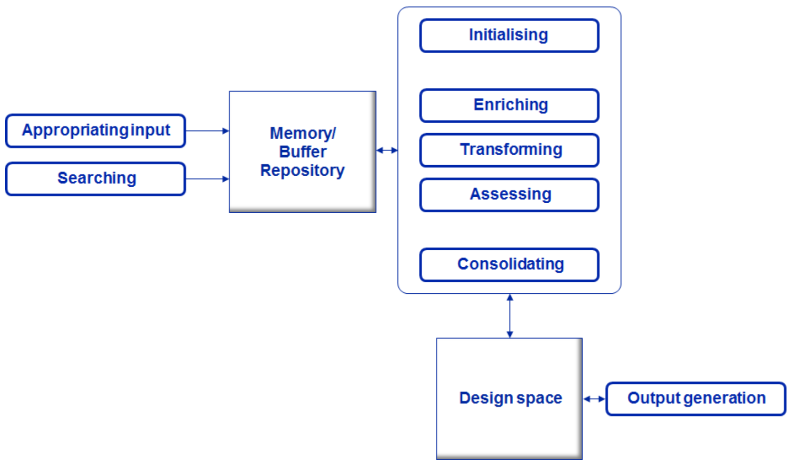

Figure 15: Design process: sub-processes

The knowledge construction process is started by defining the target content of the design space i.e. the deviations as compared to the nominal target content.
It is continued and executed via three sub-processes: enriching (the content of the different areas of the design space), transforming this content as needed and assessing the content, in each area and between areas, for consistency and completeness.
There is also a consolidation process that records the content of the design space in order to ensure continuity of the design process.

3.6.4.3 The evolution of the design space

During design, the content of the design space changes continuously further to the enrichment of the respective areas, further to the modification of the content of the areas, for instance, by merging the properties of two candidate artefacts, and further to the verification of an area, for instance, of the consistency of the set of constraints or the verification of the compatibility of the artefact with the design criteria.

The evolution of the design space is characterised by state transitions of the design space: any change brought about by any of the design sub-processes changes the state of the design space:

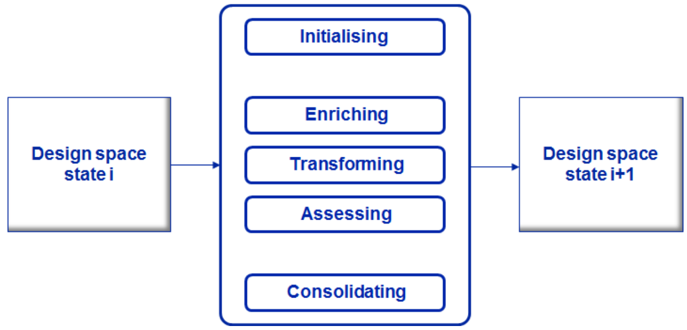

Figure 16: State transitions of the design space

The overall evolution of the design space is a follows:

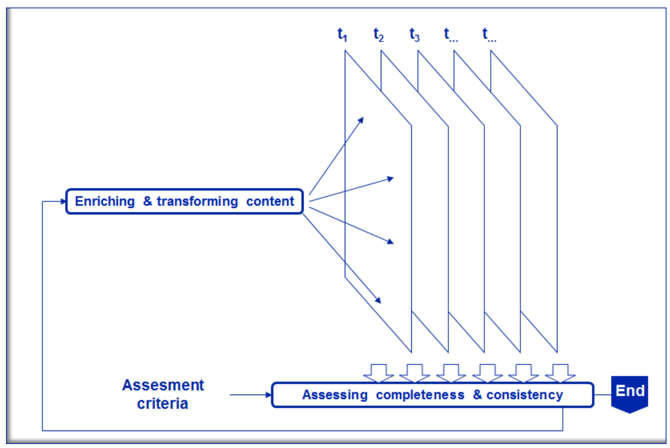

Figure 17: The evolution of the design space

In this schema, one plane represents the design space at a given moment t_i: the design space changes because the configuration has changed: the content may be enriched (for any of the design or transformed suppressing, modifying, merging or decomposing elements, or because relations between elements have changed. This assessment can be continuous or it can be carried out at the expected end of the process or at regular points (checkpoints) in the course of the design process. This is done through an implicit or explicit supervisory process[9] that verifies whether the design space is sufficiently complete and consistent so as to allow the termination of design.

[9] It is important to notice that design process management is not included in the fundamental design process. It is considered to pertain to project and process management and more specifically, to the management of the design phase

This level of acceptability is defined by the designer, and if made explicit, by criteria that pertain (a) to the design task definition, (b) to the design criteria themselves (c) to the needs for verification and validation and justification and, (d) to the needs for realisation.

3.6.4.4 The inputs of the design process

The design process starts on the basis of the initial definition of the project intent and the identification of the artefact(s) that is part of the definition of the To Be situation. This definition of the artefact can include some initial design provided by different people, for instance by the sponsor and by key stakeholders.

The other input to the design process is the 'external' knowledge i.e. knowledge that is not immediately available to the designer(s) involved. This external knowledge has to be sought in all kinds of sources including people like experts, and has to be appropriated by the designer(s).

In our view, inputs are not a given. If we assume that the design process is carried out by some kind of system (a single designer, a design team or an extended organisation with different teams), the need for input will depend on the information needs of that system. If the system has sufficient knowledge no search for input will be done. In most cases however, inputs will be available such as an early definition of the artefact and a set of basic requirements. In such cases, the inputs have to be appropriated: the inputs are pulled by not pushed into the processing system.

3.6.4.5 The outputs of the design process

Very often, there are *intermediate* outputs of the design process: notes, sketches, tentative drawings, useful for reflection (feedback on cognitive processes), for memorisation from one design session to another, for communication & collaboration and in the case of provisional and partial specifications, for review by people who are not the designer(s).

The *final* output acts (a) as a basis for the justification of the design decisions, (b) as an input for realisation, (c) as an input for artefact life-time management (preparation of the future artefact environment, communication to and training of stakeholders, first version of guidance for users and operators etc….) and (d) as a contribution to the project justification, for example, with a business case supporting the decision to proceed with the next project phase, or to life-cycle costing.

The explicit character and the actual content of the design results are strongly conditioned by the project context. The primary content consists typically of: (a) the definition of type of artefact, (b) the rationale that defines the nature and the function of the artefact, (c) the artefact description(s) that support the representation and the appropriation of the artefact by the different stakeholders with information about feasibility resp. optimality of the artefact, (d) artefact specifications i.e. descriptions, models, decomposition (breakdown structure) and sizing, oriented towards realisation, (e) the anticipation of the realisation of the artefact for justifying the realisation feasibility resp. optimality as well as realisation processes and instructions, (f) the anticipation of the artefact life-time in terms of scenarios or narratives that describe the properties and behaviour of the artefact in relevant contexts (normal or exceptional) so as to ascertain the operational feasibility resp. optimality, maintenance feasibility resp. optimality and disposal feasibility resp. optimality. This output may be accompanied by additional design information such as: a design process rationale explaining how the design process was carried out, the expression of the comprehension of the needs by explaining how the project intent and the requirements of the artefact have been understood.

All these outputs are expressions of the content of the design space at a given moment. They are expressed through some kind of formalism (for example, drawings with appropriated symbols, or a language with a specific vocabulary that is influenced by the particular design discipline). This formalism may impose also a given syntax and hence, the design outputs are frequently incomplete and distorted up to a certain level as compared to the original thoughts.

After completion of the design process, design outputs may be archived as potential proof of what was intended (and maybe not realised as intended) or what has been discovered (a basis for patent application), or be used also for sharing knowledge across projects.

3.6.4.6 Design strategies

Given the nature of the design process, different designs strategies can be characterised: (a) problem solving approach to understand the needs and to provide a solution (the artefact) to these needs, (b) invention without an extended problem solving activity or with only a weak feeling about some future need without further reflection[10]. Working with a hypothetical artefact can be useful for exploring the type of design criteria that might be applicable and for identifying potential issues of feasibility, optimality, and all other '-ties': maintainability, usability, disposability, ….

These strategies appear to be aligned with thinking modes that have been observed among designers (Lawson, 2007): problem analysis mode and (solution) generation mode, junior designers leaning more towards analysis while more experienced designers have a preference for the latter. A stated before, this appears to refer to the three main areas of the design space. In enriching the areas of the design space, attention be focused on (a) the analysis of the 'problem[11]' i.e. the project needs, the requirements for the solution and all kinds of applicable criteria, including constraints, to be applied so as to verify the adequacy of the artefact and on (b) the artefact or artefact alternatives that may offer the 'solution' to the problem. With the definition of the third main area of the design space, a third option appears: (c) the

[10] The Russian composer Stravinsky once said that artists (and probably inventors too), define for themselves the problem they want to solve, in frequent cases to challenge themselves.

[11] In general terms, a problem can be defined as the gap between the AS IS situation and the TO BE situation. Hence, the 'problem' is not necessarily a problem in the usual meaning (frustrating, related to unacceptable conditions in the As Is situation) but it may result from the ambition to improve the present situation or to move to an 'ideal' state.

analysis or simulation of ‘what-if’ situations for the realisation and further phases in the life-time of the artefact.

An important design strategy consists of decomposing the artefact in parts. This requires an overall design to be made, followed by the design of each of the parts and the integration of the different design into one.

3.6.5 Key statements

Definition

- The design process is the abstract model of activities to be carried out to fulfil the purpose of design namely to construct knowledge about the artefact and to ascertain that it will contribute to achieving the project objectives. The model is abstract in the sense that no reference is made to the type of artefact that is dealt with or to the resources involved for carrying out the design process.

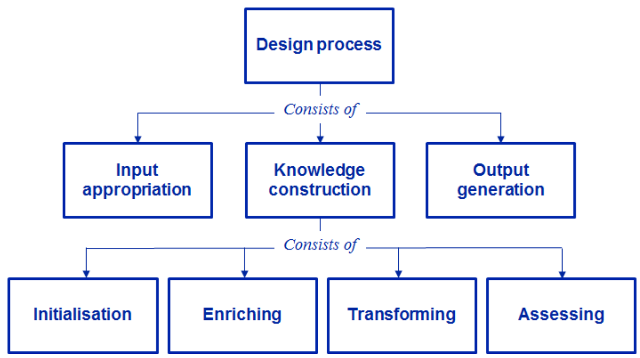

Figure 18: Key concepts of the design process

Statements

1. The essence of the design process is to build on the knowledge available at the start and to enrich it up to a satisfying level of completeness and consistency. The satisfaction criterion is the acceptable level of uncertainty that remains at the end of the design process.
2. The design process consists of three main sub-processes:
   - The appropriation of input available at the start of design or resulting from information searching
   - Knowledge construction, that consist in itself in one initialisation and three sub-sub-processes
   - Output generation: producing intermediate and final design results.
3. The design starts with the initialisation of the design space, given the project intent and the objectives set forward for design.
4. The recurrent knowledge construction sub-processes are:
   - Identifying design criteria i.e. all the elements that help for validating the adequacy of the description of the artefact.
   - Defining and refining the definition of the artefact and describing its properties as designed artefact.
   - Anticipating the artefacts realisation and the further life-time stages of the artefact.
5. There is a priori no pre-determined sequence inherent to the design process. There are dependencies between sub-processes:
   - The logical dependencies between design space areas
   - Dependencies that are inherent to the nature of the artefact

- The dependencies inherent to the approach chosen, if any, for executing the design process.

6. At each change of an element of the design space or its relation to other elements, the design space changes. These changes go in parallel with the execution of the design process until a sufficient level of completeness and consistency is achieved.
7. The evaluation of completeness and consistency against the reduction of uncertainty is done by the designer on the basis of subjective or objective (external) criteria.

3.6.6 Example

An improvising mono-designer

An individual designer, working alone, may have a holistic view on the design space but reduce the target content by focusing essentially on the artefact. He may have an intuitive perception of the needs he wants to address without having specific users in mind.

Where the artefact is concerned he may fill on the function and embodiment sub-areas and, at least at the start, forget completely the ergonomic aspects of the artefact. For the function and the embodiment sub-areas, he may enrich them as his ideas come to his mind. To an external observer, this may appear as chaotic but the basic order in the process is that from time to time, the designer assesses the completeness and the consistency of the design i.e. the content of the design and also identifies knowledge gaps. He will try to complete them, on the basis of his personal knowledge or start a search for external knowledge.

A professional designer applying a mandatory methodology

A professional designer acting in a formal design organisation will use the mandatory design method, if any. He will address the different areas of the design space according to the sequence imposed by the standard method.

If, at the start of his project, he has no idea about the future artefact, he may encounter some difficulty in gathering requirements and sort them out in applicable and non-applicable requirements. As the definition of the artefacts evolves, the requirements will become more focused.

He will make intermediate assessments and from time to time, as identified at the moment the design task was assigned to him, he will have his work reviewed by others.

3.6.7 Discussion and conclusion

The proposed theory deals with the essence of the design process i.e. to complete and make consistent in a satisfactory way, the design space i.e. the knowledge that will reduce the uncertainty of the project. It does not imply any inherent sequence for completing the respective areas of the design space.

Moreover, it takes into account the starting position in terms of pre-existing knowledge which depends on the designer(s), on the case at hand and on the preliminary work carried out before the design phase(s).

3.7 The design organisation: instantiating the design process

3.7.1 Introduction

The design process is an abstraction: it is a model that is to be adapted to the various different design situations, depending not only on the project wherefore design is performed but also on the specific resources involved in the actual execution of the design process.

The purpose of this contribution is twofold: (a) to address the organisational context wherein the design process takes place and (b) to look in more detail to the mechanism by which the design process model is made real – is instantiated – by involving a set of resources, human beings possibly supported by tools. In addition, some clues will be indicated as to how the design organisation influences the translation of the design process in tasks to be performed by the available resources.

The contribution does not aim at the detailed description of the different types of design organisations and their characteristics. No distinction will be made between an individual designer and a design team in performing design. In other words, the dynamics of a design team, that exist in reality, will not be addressed

3.7.2 Related work

Design literature pays a lot of attention to the way design organisations work. Literature on design organisations are not that frequent; the same can be said about the mechanisms of allocation of design tasks. An obvious explanation is that these themes are often dealt with by research about projects and project management which however, does not look to the specificity of design in this respect. It should be clear that in relation to a project where a design phase is defined, and where the design phase is to be performed by several designers, an individual designer only executes a particular design task, for example about a component of the artefact and that the integration of the results produced by the different designers has to be carefully dealt with.

For this section, the related work pertains to the mechanisms of tasks allocation, the team behaviour, the aspects of organisational structure and culture that may affect, not only the definition of the tasks but also their execution, for example, in terms of preserving institutional interests, team behaviour and in decision making.

Design task allocation needs to be done when implementing design process in a real design project. Wong (2009) uses a modification of the Balanced Scorecard framework devised by Norton and Kaplan (Norton, 1992) for optimising the design objectives. The framework has four dimensions (as the original) but the topics have changed into: aesthetic perspective, functionality, build-ability and economic perspective. It belongs to the domain of architectural design. In our view, the number of topics of dimensions is somewhat arbitrary: one can easily imagine that there are other concerns for example, performance, or the three dimensions we have defined for function, or even, the interfaces with other design tasks to be kept in mind. The concept is however interesting for making designers aware of the balance to be sought between key aspects of the design task and the design content.

Working in teams is not proper to design. Design teams do not simply work, they communicate and collaborate. Stempfle (2002) addresses the concept of thinking in teams, involving problems that emerge and that have to be solved, the lack of common understanding which occurs frequently in multi-disciplinary teams due to the differences in background, disagreement and challenging of ideas, and so on. One can add to it the relations within the team with natural leaders who may become dominant at the risk of not exploiting the knowledge and experience of more introvert team members. Kleinsmann (2008) has studied the barriers and enablers for creating shared understanding in a co-design project and has identified factors at the agent level, at project level and at company level. Adams (2010) examined the social and behavioural influences in team processes and proposed a hierarchy for social and behavioural development climbing up from self-identity, social identity to group emotion, group mood and emotional intelligence. (Effective) teams are in fact systems where the overall behaviour transcends the behaviour of the individual members.

Concerning *Organisation structure*, an organisational view on design communication has been studied by Chiu (2002) in the context of architectural design. He identifies four communication problems: the media problem and the symbols being used, the semantic problem and the possibility of interference and noise, the performance problem and the effect of the communication on the perception of the meaning and its influence on the receiver's behaviour and finally, the organisational problem in reaching the right persons for sharing expertise and ideas.
The design organisation can be fragmented (different departments or different firms). It is obvious that a professional designer involved in decision making may lean towards decisions that are justifiable as design decisions but that also serve the interests of his organisation. Hence, if different organisations are involved in design, inconsistencies may appear.

Organisation culture usually has important impact on design results. There are different definitions of organisational culture. (Schein, 1990) defined organisational culture as a pattern of basic assumptions that are invented, discovered, or developed by a given group as it learns to cope with problems of external adaptation and internal integration and that have worked well enough to be considered valid and, therefore, taught to new members as the correct way to perceive, think, and feel in reference to those problems. Other definitions were proposed by (Drennan, 1990), (Hofstede, 1997), (Ouchi, 1981) and (Pascale and Athos, 1982). Culture and the organisational traditions influence the behaviour and the decision making by designers. In addition, (Belassi, 2007) examined the effects of organisational culture on new product development projects: organisations that wish to be successful in developing new products must have a positive work environment with strong management leadership. (Eskered, 2007) focuses on the impact of the organisational culture on the knowledge transfer between project managers: the key contribution the paper is pointing out is that project orientation facilitated knowledge silos and 'lonely cowboys' that is in certainly not favourable to knowledge exchange between design teams.

3.7.3 Key concepts

A (design) *resource* is any person or any kind of device capable to perform part of the activities required by the design process.

The *design organisation* is the set of resources that cooperate so as to perform all the activities required by the design process. The design organisation, during the design phase is a part of or equivalent to the project organisation.

Instantiation is the act of creating an 'instance' i.e. a particular case of the design process. It implies making real the design process for a particular project, a particular artefact and a particular set of design resources, by adding specific information to the design process model.

3.7.4 Rationale

It is the design organisation that executes, with its different resources, the instantiated design process i.e. the design phase. In this perspective, the rationale below deals with:

- The variety of design organisations and forms of design
- The instantiation of the design process (instance)
- The possible impact of the design organisation on design.

3.7.4.1 The variety of design organisations and forms of design

<u>The variety of design organisations</u>

The variety of the design organisations is considerable: at minimum, there is the lonely inventor who has only imagined users in his mind and who designs and realises himself the artefact. At maximum, one can think of a complex design organisation where one firm acts as integrator and where many other firms are sub-contractors or better, co-designers for designing and quite a complex artefact. The design of the Boeing 777 was such as case (Sabbagh, 1995).

The main variation factors for characterising the design organisation are: the number of people involved, their respective roles, the number of sub-organisations involved, the tightly vs. loosely coupling of these sub-organisations (an integrated firm vs. a time-limited consortium of companies and independent consultants.

Hence, design organisation can consist of a single designer, a team organised so as to carry out a design project, a design department (for example, within a manufacturing enterprise), a consulting or engineering bureau specialised in design and work supervision.

By extension, one may consider the stakeholders as a part of the design organisation, depending on how they are involved: ad-hoc or strongly involved in the design process for the definition of the requirements, for reviewing the design proposals and even for active involvement in design (participative design).

<u>Design organisation and forms of design</u>

From the above, we propose the following forms of design:

- *Autonomous design*: when an autonomous single designer who undertakes a project including design and realisation, at least partially. This is typical for the inventor.
- *Commissioned design*: when a single designer undertakes a design project on behalf of a sponsor or client. This is typical for a single designer working for one or more clients. Commissioned design leads, at least in professional situations, to a higher level of formalisation as compared to the autonomous design situation, at least where the design results are concerned.
- *Organised design*: this is a further extension of commissioned design when an organised group or several groups of designers undertake a design project for one or more client organisations. There is more differentiation in the roles pertaining to the design process: users, operators, people in charge of maintenance and people in charge of disposal. This is typical for professional design in more complex situations.

3.7.4.2 From design process to design task: instantiating the design process

Instantiating the design process establishes the link between the design process model and the design activities to be performed by the available resources.

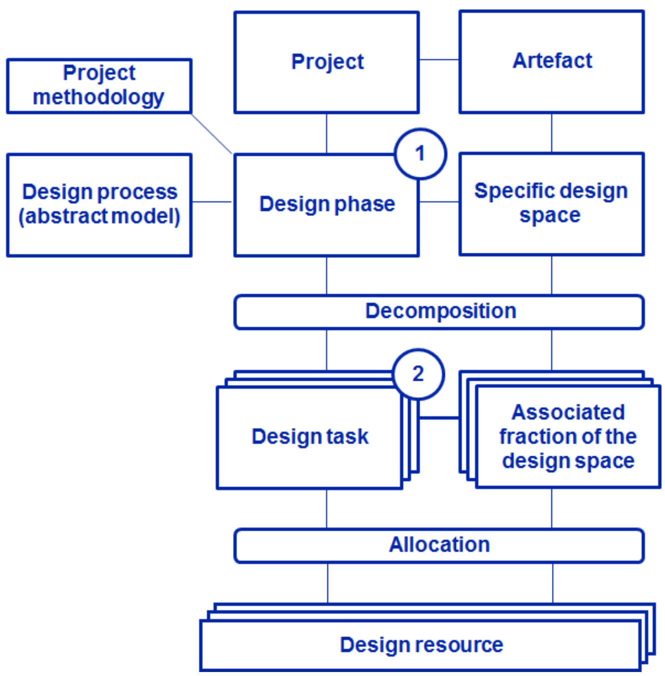

Figure 19: Instantiating the design process

In design, there are normally two level of instantiation of the design process model:

- Level 1 where the design phase(s) is (are) defined with its specific goals. This is done on the basis of the project objectives, the specific artefact and using the project methodology.
- Level 2 where the design phase as a whole is decomposed into tasks that are allocated to the different design resources.

The instantiation of the design space is done in parallel.

The level of detail or explicitness in the tasks definition can vary considerably depending on the design situation both in the allocation of the design task and as well as in the planning and the preparation by the designer or design team.

Definition and allocation of the design task (by the sponsor or client): the design task is defined through a possible an early definition of the artefact, the overall project objectives, the specific design objectives (the whole or a part of the artefact, the areas of the design space to be dealt with and/or the target content of the expected design results, the constraints (for example on the task duration), the applicable norms and standards, the available resources (people and tools) and the organisation of the task (task monitoring, milestones, reviews, …). When different design tasks are allocated to different designers if is normally up to the sponsor or design manager to ensure that the design results of the respective tasks fit each with other.
In autonomous design, the designer defines the design task for himself.

*Appropriation and planning of the execution of the design task (by the designer or the design team): w*hen the design task is appropriated by the designer or the design team, it may be wrongly understood. On the other hand, the designer resp. the design team may have a design intent that goes beyond what is asked: the designer's ambition can trigger innovation. Hence, design is not merely the passive execution of a design task.

The appropriation of the design tasks leads to the initialisation of the design space, for the specific designer resp. team and the particular task. This initialisation implies the definition of the target entities (areas and sub-areas in the design space for the (part of the) artefact he is in charge of. He may complement his own working memory with representation tools at his disposal: white board, computer, paper for notes.

In the section about the design process, it has been stated that there is no a priori sequence to be followed in the design process. The designer resp. the design team may have to use specific standards and methods, referred to at the moment of task allocation or simply imposed in the design organisation. If not, they may choose a self-developed method for organising the work. In addition to facilitating communication and collaboration, a method may have the benefit of reducing the complexity of the design process by creating sets of subjects that can be dealt with separately, in successive steps.

<u>Executing the design process</u>

As with the instantiation of the design process, two perspectives are to be considered: the design task management and the designer's activities. The first perspective pertains to task and project management involving planning and re-planning, monitoring and evaluation. They are not developed here. The latter perspective is the ‘real-time’ view of the designer on his activities. They are analysed in detail in the section about the designer’s activities.

A design is very rarely performed in one single session. Hence, most often, there is a sequence of design sessions where the designer (design team) actively designs, separated by periods where the designer either is involved in other activities that have nothing to do with the design at hand, or where the designer is still involved with the design but in an off-line mode. Some designers become so ‘obsessed’ by the design in such a way that their design activity is nearly permanent and goes on between design sessions: “they go to bed with their design”.

In commissioned design and in organised design there may be an explicit need for justification of the design decisions and the process decisions (for example, the decision to proceed with the design task or to terminate it). Depending on the reputation of the designer(s), the sponsor(s) may request two kinds of justifications: the one pertaining to the design decisions made (Why is the specified artefact the best among all possible?), the other with respect to the continuation of the project (On the basis of what is known at the end of the design task, is it worthwhile to proceed further with the project, given the expected benefits, the costs and the anticipated risks?). The designers may provide a recommendation but obviously the sponsor decides.

The design process is terminated when: (a) the design is considered to be complete as to the task objectives, as to the adequacy (feasibility, optimality) of the design artefact, as to the requirements and more generally, as to the project intent or as to standards that define the contents of the target results, (b) when the remaining uncertainty[12] (depending, in part, on the uncertainty the design organisation is willing to accept (before moving to prototyping or realisation) is considered acceptable, (c) when the design resources and/or elapsed time are exhausted , (d) when there is divergence and/or lack of solution (non-feasibility) or (e) by an external decision affecting the project.

On the side of the design manager, the task execution by the designer(s) is accompanied by communication task monitoring and management, schedule management, resources management and coherence or integration management across tasks. Since task management at manager and at designer level is not included in the present theory, this is not further developed.

3.7.4.3 The impact of the design organisation on design

The design organisation influences the design activities in different ways: by imposing the design strategy and methodology, by bending the translation of the project intent in the design intent[13] and into design

[12] It is recalled that uncertainty can be interpreted differently: (a) as presenting a risk, or (b) offering opportunities. The interpretation depends on the attitude of the observer resp. actor.

[13] The design intent (by the designer or design manager) can deviate from the project intent (by the sponsor or the project manager) by being creative and audacious and, by innovating instead of a minimalistic interpretation of the project intent.

decisions, by the organisational culture (values), by the way uncertainty is dealt with and by imposing constraints, for instance, on the realisation process and resources. More specific factors are:

Type of design organisation	Factors that influence the design
Mono-designer	• Individual knowledge and experience • Personal preferences and personal ambition • Attitude towards risk and innovation
Design team	• Team knowledge and experience • Respective dominance of team members • In joint creative thinking, the possibility of the team members to voice their ideas and concerns • The openness towards stakeholders and their participation in the design activities
Design department	• Department's knowledge and experience • Formalised design methods and standards • The level of formalisation in communication and collaboration • The existing hierarchy and the way decisions are made • The reputation of the department within the organisation • Institutional interests and departmental culture
Autonomous design bureau (For example, an engineering consultancy firm)	• Organisation's knowledge and experience • The reputation of the organisation • Organisational culture • Commercial or institutional interests

Table 4: Design organisation factors that influence design

3.7.5 Key statements

Definitions

- The design organisation is the set of resources that cooperate so as to perform all the activities required by the design process. The design organisation, during the design phase is a part of or equivalent to the project organisation.
- Instantiation is the act of creating an 'instance' i.e. a particular case of the design process. It implies making real the design process for a particular project, a particular artefact and a particular set of design resources, by adding specific information to the design process model.

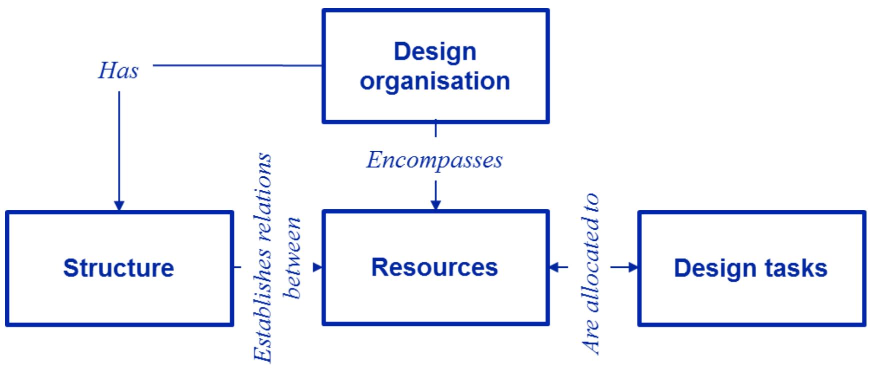

Figure 20: Key concepts of the design organisation

Statements

1. Depending on the nature and the structure of the design organisation, three typical forms of design are identified:
   - Autonomous design: when an autonomous single designer who undertakes a project including design and realisation, at least partially. This is typical for the inventor.
   - Commissioned design: when a single designer undertakes a design project on behalf of a sponsor or client. This is typical for a single professional designer working for one or more clients.
   - Organised design: this is a further extension of commissioned design when an organised group or several groups of designers undertake a design project for one or more client organisations.
2. To become real, the design process has to be instantiated through the definition and the allocation of one or more design tasks, to one or more designers resp. design teams.
3. Instantiation implies the decomposition of the design phase into tasks, each task having a specific objective. The designer(s) have to appropriate the task for design to become effective.
4. The definition, the allocation, the appropriation and the execution of the design tasks is influenced by factors pertaining to
   - The designer himself
   - The design team, if any

- The design department, if any
- The design organisation.

3.7.6 Example

Reference to organisation problem as see by an organisation specialist, a psychologist and an IT specialist

In the domain of information systems an old story goes as follows. A general manager was having problems with his organisation. He consulted three experts: a psychologist, an organisation expert and an information technology expert. The first identified relational problems within the organisation and offered assistance in resolving them. The second expert came to the conclusion the structure of the organisation had to change and proposed an action plan to do it. For the information technology specialist, it was obvious that the information system was obsolete and that the information flows has to be revisited and the technical platform to be renewed.
These are obvious influences at designer’s level.

Engineering bureau

In relation to the issue of uncertainty and more specifically risk, an engineering bureau may tend to stick to proven solutions and not investigate the most rewarding solutions. On the other hand, when working in the framework of a fixed-price contract, the bureau may tend to have a limitative interpretation of the scope of the project resp. of the artefact in order to be safe where projects costs are concerned. Hence, not only the different organisations involved in a design but also their (explicit) relations influence the design.

3.7.7 Discussion and conclusion

The abstract design process model is to be instantiated to become ‘real’. Information about the particular project and artefact has to be added. A further step is to partition the instantiated design process (which is often the design phase of a project) into different design task that are allocated to the different available resources (designers).

The design tasks, as defined and executed are subject to influences (for good or for bad) at different levels: the designer, the design team, the design department and the for-profit or non-profit organisation.

3.8 The designer's activities[14] : a cognitive approach

3.8.1 Introduction

After analysing the instantiation of the design process onto one or more design resources (one designer, several designers, design teams or organisations), one has now to examine what happens at the level of the individual designer. The previous sections: the project, the design process and the design space, are external to the designer: in other words they are observational, even in the case of the designer observing what he is doing. In addition to these external viewpoints there is a need for explaining design from the perspective of the design-in-action. Yet, in the present contribution the intention is to go further and to develop a designer-centred analysis and to link the design activities that derive from the instantiated design process to the mental resources a designer can mobilise in order to perform his design task.

The set of activities that the designer deploys during design is briefly discussed. However, it should be noticed that the essence of the present contribution is about the designer's cognitive activities. They appear to at the core of design.

3.8.2 Related work

In design literature, it is relatively rare that a clear distinction is made between the (abstract) design process and the cognitive activities as carried out by the designer: in many cases the two perspectives are merged and in other cases, the cognitive processes are dealt in a general manner that does not show a clear link with the design process. They are nevertheless valuable in contributing to a better understanding of design. Among these contributions are these about:

Cognition in design. 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 pro-cessing. 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 was indicated by (Visser, 2006a) 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

[14] The present contribution is a updated version of the paper presented at the MOSIM'12 conference: Huysentruyt, Lespinet-Najib, Chen. A model of cognitive activities in design_version 2.0. 2012.

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, 1979) provides an understanding of the importance of the 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).

Visser (1992a) 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. 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 pro-cessing in order to achieve the goal of the action’. In later work, (Visser, 2006b) stresses the nature of design as being not only problem solving but 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.

The dynamics of the design process. This deals with the designer-in-action. (Maher, 1996) addresses the alternating between working on the problem space and working on the solution space, both spaces evolving in parallel. Along similar lines, (Cross, 1994) in a problem solving approach and (Pugh, 1991) when dealing with the process of concept generation and selection have identified steps in the design process where divergence and convergence were alternating, ultimately converging to the right solution or to the selection of the most adequate concept. It is clear that design, as carried out by the designer, is a highly dynamic process that goes beyond a simple sequential execution of steps.

Evaluation criteria: aesthetics. In the contribution about artefacts and the function of artefacts, the latter has been defined according to three dimensions (identity-related, relational and technical). The technical function is the closest to be measured in a quantitative way, the other dimensions being less easy to quantify. These domains are closer to psychology and sociology. One of the aspects that touch both the identity-related and the relational dimensions is aesthetics. (Folmann, 2010) defines the two aspects of aesthetics in design: design as a sensual appearance and design as an act of communication. He has developed a framework that can be used in analyses and discussions about aesthetics. It might be investigated whether these ideas can be a sources of inspiration for dealing with the three dimensional aspects of artefacts.

Creativity. In design literature a lot of attention is paid to design creativity, which on itself is a whole domain of research. (Yong Se, 2011) studied the relations between design activity and personal creativity modes. He came to the conclusions that the designer having feeling-oriented personal cognitive characteristics used much external knowledge and many general features, and put an emphasis on problem understanding and early idea generation phases rather than design elaboration phase. The designer with the organising creativity mode could be associated with rich intent information category that is related to the management of the design process. The designer having the factual-oriented mode showed the tendency to conduct design elaboration with an extroverted character. The designer characterised by the perception-oriented mode had the trait of the scheduler and was concentrated on problem understanding and process management. This can brought in parallel with (Wilde, 1999), who examined the roles in design teams and made the link with eight personal creativity modes.
(Vicente, 2012) has paid attention to the relation between creativity in association with design methods and comes to the conclusion that idea-generation methods, for example, brainstorming, provide more novel outcomes while on the other hand, functional analysis as a structured method, provide the best outcomes in terms of usefulness.

*Search. S*earch is a means to acquire new information or to explore alternatives that have not yet been considered. (Fricke, 1996) examined the individual approaches in engineering design and identified three types of concept generation: excessive expansion of the search space (or scope), a balanced search and an unreasonable restriction of the search space.

Both references on learning and search illustrate the fact that although humans are equipped with similar ‘information-processing hardware’ it is expectable that design behaviour is actually influenced by the personality, the knowledge and the experience of the individual designer. In this respect, in the sources that have been examined, except for (Simon, 1996) no clear reference was made to the fact that knowledge and experience is up to a certain point, relative to the design task at hand. In the same way, no mention was made of the starting conditions of a design task were strong differences may exist in terms of already available knowledge. We have defined design as knowledge construction. Obviously, it is knowledge construction on the basis of pre-existing knowledge.

3.8.3 Key concepts

3.8.3.1 Designers activities

A designer ‘in-action’ is involved in a series of *activities* that for the sake of simplicity are grouped in three categories:

- The *cognitive* (mental) activities i.e. the process of information processing called 'high level', pertaining to memory, attention, etc., the more elementary processes such as perception and those involving motor skills;
- The *expression* activities whereby the designer expresses by writing and by drawing on some medium (paper, whiteboard, computer), part of the contents of the working memory which is one of the types of memory (this will be detailed later);
- The *interaction* activities whereby the designer interacts (a) with other people (designers, users, etc…), (b) with the physical world (objects), (c) with information sources (documents, data-bases, …) and (d) with tools that may combine different capabilities such as recording, information search, representation, drawing, computation, simulation, document and knowledge management…

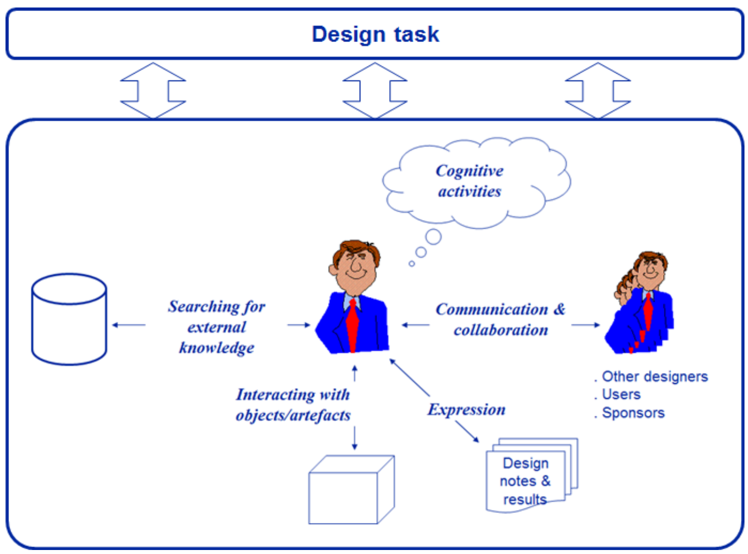

Figure 21: Designer's interactions during the execution of the design task

It is obvious that an additive approach (such as with linear system models), whereby the effects of the different designer's activities are simply cumulated, is a simplification. Indeed, there are without a doubt (a) interactions between expression activities and communication and collaboration with people and (b) retro-actions such as during the expression of design ideas that helps in structuring these ideas in the mind of the designer. It is our conviction that by better understanding what happens at the level of the single designer, it will be possible to build on this knowledge and to better understand the interactions between individual and group behaviour.

3.8.3.2 Cognition and the cognitive task

<u>Cognition</u>

The notions of *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 stable (internal) representations of knowledge. 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 life-time through perception, interaction with the world and internal processing.

Cognitive task

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

3.8.3.3 A model for cognitive tasks

Assumptions

The model is based on a series of assumptions:

- The mind learns through information acquisition and integration into the pre-existing cognition i.e. by 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 i.e. meta-cognition; for example, the mind may develop a discourse upon a series of events experienced by the individual.

The model has a series of components that result from a reasonable consensus in cognitive science:

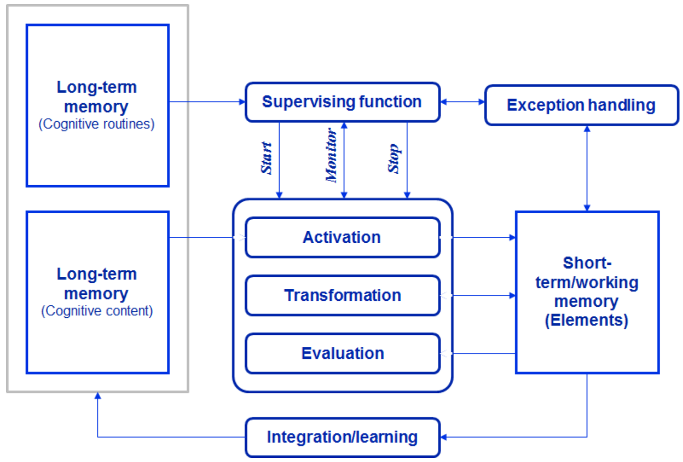

Figure 22: A model of activities in a cognitive task

The proposed model is represented in the above figure. 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 (integration/learning),
- On the choice and the content of the routines: through the exception handling process.

Note

The proposed model appears to be similar to the one proposed by (Newell and Simon, 1972), the IPS (Information Processing Model). However, there are important differences:

- The processes activation, transformation and evaluation are explicitly defined, while the supervision process, the exception handling process and the learning process have been added.
- The distinction is made between cognition content and cognition routines,
- Cognition is proper to each specific person and hence, varies from one person to another. Objective information and methods have to be appropriated so as to constitute a personalised version for each person.

As shown in the above figure the model consists of:

Model components

The *long-term memory* that encompasses:

- *Cognitive content (knowledge):* this memory consists of the perceptive memory with contents pertaining to 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'). In physical product design, two types of elements are present: verbal-conceptual (Vygotsky talks of internal and external speech) and visual-graphic (Cross, 1996). However, this may be a restrictive as it is associated with a specific design domain and not necessarily valid in other domains of design such as in service design or in arts

Where objects are concerned, cognition consists of perceptual and motor cognition gained through the five senses, declarative cognition i.e. cognition consisting of symbols (for instance, expressed in some kind of language), and meta-cognition: cognition built-upon the types of cognition mentioned above, such as models and theories. The term 'meta' is relative: meta-cognition can be built upon meta-cognition etc.

- *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 elements 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 elements 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).

The nature of the cognition elements in the working memory is diverse: episodes or elements of episodes that are re-activate including representations of objects, rationales expressed in some kind of formalism (structures of statements such as logical categories, models and theories that establish logical relations between elements) and references to own cognition or to external sources.

Cognitive processes

Cognitive processes are abstractions for the sets of routines (processing capabilities) that are proper to a given person. Conversely, a routine can be considered as an instance of a given cognitive process. The cognitive activities correspond to the routines as they are executed in real time. They establish the relation between the content of the long-term memory and the content of the short-memory. For each category of routines, there is at least one routine that a person can apply namely trial-and-error.

The *core* cognitive processes or classes of routines for a cognitive task are:

- The *activation* of content in the cognition in the long-term memory that is equivalent to the projection in the short-term memory as one or more cognitive elements. In some cases, two design processes are carried out quite in parallel[15]. This is an example of looking to other sources of inspiration (cognition activation) not related to the design at hand.
- The *transformation* of elements 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 element, at the level of a set of elements or between sets of elements such the comparison of alternatives. The minimal evaluation is acceptance or rejection of a given element as being acceptable or not. More explicit evaluation involves comparison between two elements or the evaluation using explicit criteria that may be associated with a method that has been appropriated by an individual.

There are three additional processes:

- The *supervisory process* that controls explicitly the execution of the core processes and their instances (the routines). Explicit supervision 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 chained routines. This may explain the development of more sophisticated routines by chaining of more elementary routines.
- *Exception handling* (problem solving): when a conflict arises, the supervision process 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 elements, 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. During execution, learning is performed through the action and

[15] See Brahms composing his symphonies two by two.

by accumulating and organising design elements[16]. This process is for a large part implicit; it may become explicit by organising a session ‘lessons learnt’ at the completion of the design activities. (See Kolb and Fry, learning cycle, 1975)

Process dynamics

A photo camera provides a good analogy for the dynamics of the working memory. Paying attention to one or more subjects corresponds to the selection of and the focusing on the object of the photography. Zooming in corresponds to decomposition and focusing on a part of the original object. Zooming out corresponds to building the ‘big picture’ that integrates the different zoomed-in pictures. Making a picture is memorising the state of a situation (the object of the photography, at a given time. The series of successive pictures builds up an episode.

The cognitive process model is a static description. In practice, the activities show a dynamic character, starting with the initialisation of the design task, the execution of the core processes in a supervised or in an automatic mode, the resolution of conflicts by exception handling and finally, terminating the cognitive task.

The dynamic character of the model in ‘real-time’ occurs through:

- The task *initialisation* (bootstrap): further to the appropriation by the agent of a task given to him by himself someone else, the working space is being initialised with the target entities that are proper to the type of task.
- The *execution* of the basic processes; activation, transformation and evaluation with the routines that are characteristic of the agent’s experience.
- The *transitions* between processes: from activation to transformation and to evaluation that leads to feedback on the activation and or on the transformation process.

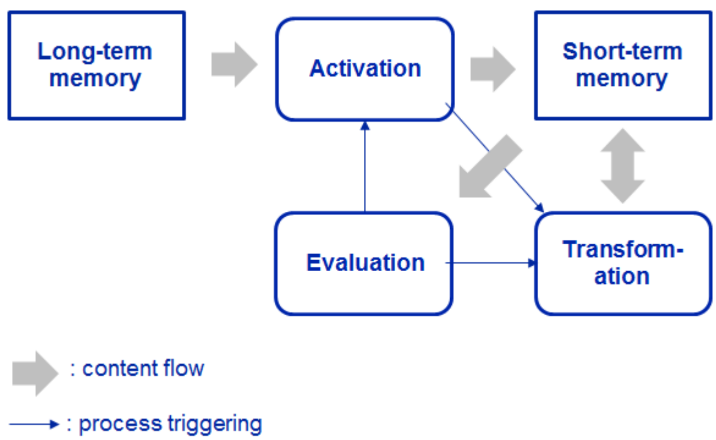

Figure 23: Transitions between core processes

[16] This does not imply that the design process is a cumulative, sequential process that leads to a “solution”. Rather, the learning is about the elements that appear useful and other that appear inadequate.

- The *exit* from the core processes when contradictions or conflicts arise and the activation of an *exception handling* process that is in fact a problem solving processes dedicated to the resolution of the problems associated with the basic task, followed by a *return* to the core process taking into account the solution that has been found to the problem.
- The *termination* of the cognitive task when the state of the working space has evolved up to a point where the level of detail (enrichment) and the level of consistency of the content of the working space is deemed sufficient by the agent involved.

It has to be noticed that these processes and events may be under control of the supervising process (conscious control) or may happen in an automatic (unconscious) manner. In the prioritisation of the cognitive processes that deal with the different themes, the notion of cognitive load (Visser, 2006) is worthwhile to consider, the idea being that agents give priority to the processes that have a lower cognitive load (expected complexity or process duration) than others. This is not always the case however; some people when tackling a subject start with the most difficult aspects of the task. This leads to an improved concept of 'cognitive costs and benefits' whereby an agent evaluates the different aspects of the task at hand and give priority to the elements of the task that present the best balance in terms of the expected cognitive load (cost) vs. the expected benefits or probability of success.

3.8.4 Rationale

The rationale is subdivided into following subjects:

- The specificity of design as a cognitive task
- The relation between design phase, design task and the designer's activities
- The relation between the design space and the designer's memory
- The expression of design results
- (Some remarks on) design expertise
- The situation of methods and reference frameworks.

<u>The specificity of design as a cognitive task</u>

Design is a specific cognitive task for it is differentiated by: the target content of the working space and by the agent with his knowledge (the cognitive content) and experience (cognitive routines) that he may activate and invoke for carrying out the task. When an agent has a new design task, the objectives are set by a sponsor, a manager or by himself, the term 'design' evokes a series of themes to be developed. This can be the nominal list of themes (as explained in the section: Design process). Depending on the agent's knowledge and experience and on the specific context, the themes may be organised differently.

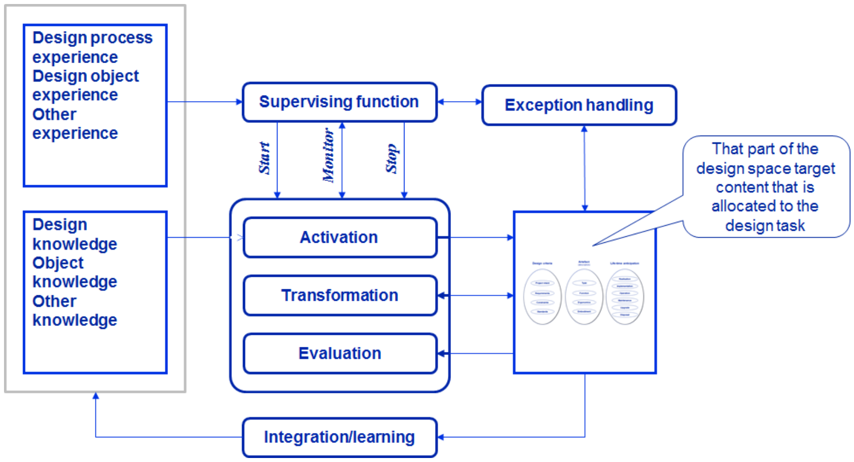

Figure 24: A cognitive process model for design, considered as a cognitive task

This qualification of design as a specific cognitive task implies that design is characterised by (a) the understanding of the task by the agent, (b) by the knowledge applied and (c) by the specific routines that instantiate the three core cognitive processes. In fact, it depends on the designer to mobilise all his cognitive resources, those pertaining to previous design tasks and those that come from other domains and that may provide original input.

Design phase, design task and designer's activities

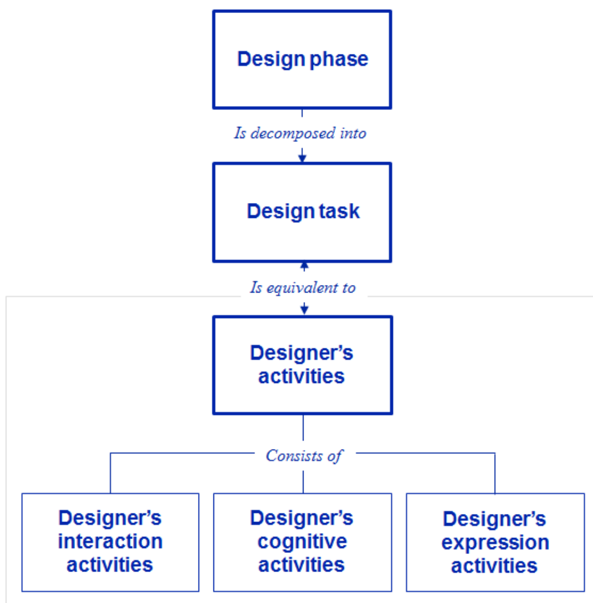

Figure 25: From design phase to designer's activities

As stated in the section on the Design Organisation, the design phase is an instance of the design process. Some projects are structured in different design phases such a preliminary design and detailed design. In such a case, there are two instances of the design process each with specific themes to be dealt with and different levels of detail and consistency to be achieved.

The design process is further instantiated by the decomposition in tasks and the allocation of tasks to resources, one of them being the designer. The execution of the design task is done through the activities of the designer: interaction activities, cognitive activities and expression activities. The different designers contribute by their results to the execution of the design phase(s).

In commissioned design, design starts with the commission i.e. with the allocation of the task to the designer. In fact, design activities may already have been started before, for instance if the designer is interested in the subject. Similarly, design activities may go on beyond the formal termination of the design phase, simply because the designer is obsessed by his subject and is still looking for a better artefact.

Hence, there must be sufficient compatibility between the design phase and the derived tasks, as planned, and the designer's activities but there is not always a strict correspondence.

The design space and the designer's memory

The short term memory of the designer contains a set of elements that are active at a given moment during design, taking into account that elements have to be activated and that they are volatile because the short term memory is volatile in itself.

Hence, the short term memory is an instance of the design space for the design task at hand; the scope may possibly have been reduced scope in terms of areas to be addressed (this depends on the task definition). It contains all the elements that pertain to a given design task, the remaining elements are considered as 'noise'. The notion of 'noise' is relative: in fact the designer may deal with two design tasks in parallel. Noise for one task may be essential for the other. Moreover, such parallel processing may be a source of inspiration by activating other cognitive content[17].

The content of the abstract design space is, at a given moment, the integration of all contents activated in the short term memory over the design task up to that moment: it is the content that has memorised in the long term memory of the designer since the start of the design task plus the content of the short term memory at that moment. The latter is the incremental part of the content of the design space.

In the long term memory, two classes of situations and episodes will be activated by priority: (a) the situations and episodes pertaining to artefacts that appear to be interesting and the interaction with these artefacts along their life-time and (b) the situations and episodes pertaining to projects done in the past, including design, as well as activities such as realisation, maintenance, etc… But this is not limitative: the creative designer will tend to go beyond the objects, situations and episodes that come naturally to his mind.

[17] Example: Johannes Brahms composing his four symphonies two by two, in parallel, although in different styles.

For teams, the abstract design space contains the shared elements of the team while the team members have their own design space (their memory). A blackboard or a flip chart is an relatively good analogy for the working memory resp. the design space (for a flip chart, the collection of all used sheets) but one should recall that blackboards and flip-charts have limitations on what they are capable to represent (merely visual): they are expressions of the contents of the working memory resp. of the design space.

A note on the expression of design content (notes and results)

The designer's memory encompasses many kinds of content. This content is the input for the expression of the design outputs (intermediate or final) through many forms: notes, reports, drawings, externalised models such a computer based representations and mathematical models,… In nearly all cases, there is selection and distortion of the cognitive content and its expression due to the cost of expression vs. the quantity of content in the mind of the designer, the formalism used (drawings, text, formulae, …) as well as the social context wherein the expression takes place (the designer will not always express ideas that are not socially correct). The design discipline whereto the involved people belong may tend to favour certain forms of expression and not others. For instance, as compared to architecture, engineering puts a strong focus on functional value (usefulness) and on measurable characteristics, and less on aesthetic considerations.

Remarks on design expertise

Similarly, the model can support the definition of a 'designer' as formulated by (Simon, 1969): a designer: " …anyone who imagines a device aimed at changing an existing situation into a preferred situation (is a designer) …". Of course, this does not mean that there are no differences between junior and experienced and expert designers (Lawson, 2007).
Conversely, a professional designer in a given domain, is somebody who has been educated and trained for a set of artefacts, technologies and methods that are proper to the domain and who been certified in some way or another. This does not mean that such as designer cannot use his knowledge and capabilities for designs that go beyond his professional domain (an electro-mechanical engineer designing a house).

Expertise derives from the projects done in the past as from the artefacts one has been exposed to. Most probably, the internal reorganisation leads to the formation of content and action schemata or patterns that can be mobilised as a whole and that allow the more experienced designer, to move more swiftly and more efficiently, provided he remains in his domain of expertise.

The designer's attitude towards uncertainty and risk is probably an important aspect of the designer's profile: innovation involves risk, not only technical but also social, when designers belong to professional communities. This is not being dealt with in the present project since affects are not considered. Another emotional characteristic that is often observed with successful design is persistence: in addition to the capability of restarting after a mishap or failure, persistence is related to the fact that design is a learning process; persistence fosters learning, allowing the designer to become more efficient as the design proceeds by applying new knowledge, often after exception handling (problem solving) and by avoiding dead-ends.

The role of methods and reference frameworks

The model of cognitive activities in design allows situating methods and reference frameworks (such as reference architectures).

Methods have to be appropriated i.e. not simply known by the designer but integrated so as to become one or several routines the designer may invoke as instances of the cognitive processes: activation, transformation and evaluation or of exception handling.

Similarly, reference frameworks and architectures define the main topics to be dealt with for designing a system that lies within their scope. Hence, reference frameworks and architectures guide the designer in defining or refining the target content to be reached for that part of design space that is associated with the allocated task.

3.8.5 Key statements

<u>Assumption</u>

- A goal-oriented cognitive task can be described by a model consisting of (a) a long term memory with content and action capabilities (cognitive routines) and, (b) a short term memory where active content is stored and which volatile by nature.
- There are three core cognitive processes: activation of content of the long-term memory in the short term memory, transformation of content in the short term memory and evaluation that triggers activation and or transformation
- There is a supervisory process that load available routines so as to instantiate activation, transformation and evaluation

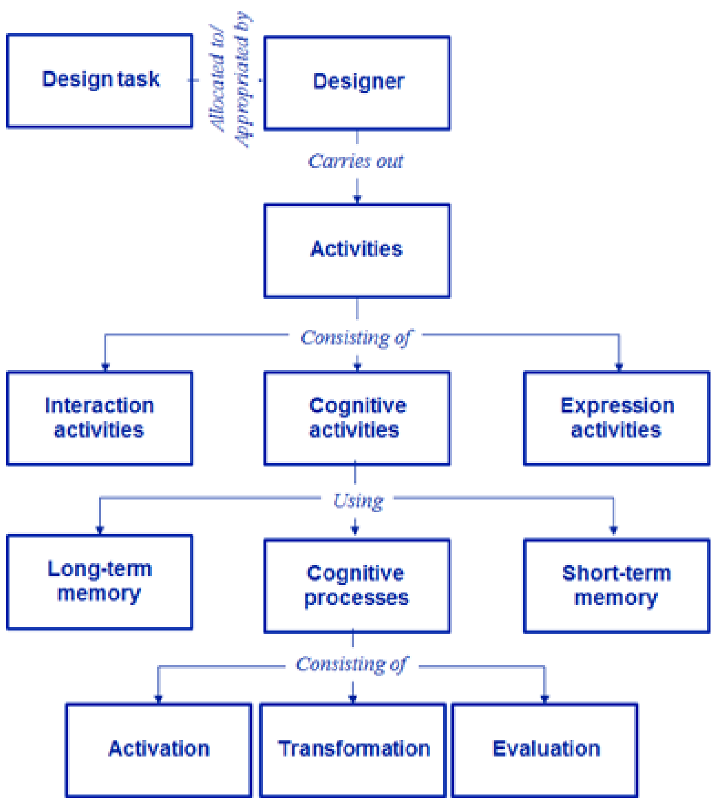

Figure 26: Key concepts of the designer's activities

<u>Statements</u>

1. The design task is the task allocated to the designer in order to fulfil his part of a design, in the context of a given project.
2. The designer carries out three categories of activities
   - Interaction activities with people, with artefacts and with tools

- Cognitive activities i.e. mental activities
- Expression activities i.e. the expression of cognitive content in terms of design outputs.

3. Where cognitive activities are concerned, design is a goal-oriented cognitive task made specific by
   - The target content to be achieved
   - The cognitive content (knowledge) being be used to achieve the target content
   - The cognitive routines (experience) being used for instantiating the activation, transformation and the evaluation processes.
4. The cognitive content (knowledge and experience) is found in the long-term memory but has to be activated in the short-term memory.
5. The three generic cognitive processes that are involved are:
   - Activation of long-term memory content in the short-term memory
   - Transformation of the content in the short-term memory
   - Evaluation of the content in the short-term memory.
6. These generic processes are instantiated (made specific) by the routines (experience) the designer has available.
7. The designer, when and as needed, explores and applies knowledge and routines deemed relevant for carrying out the design task. This knowledge and experience may be design-related but it can be any other knowledge and experience.
8. External knowledge has to be appropriated i.e. acquired, restructured as needed, and integrated before becoming part of the designer's knowledge and experience.
9. By completing and making consistent, up to a satisfying level, that part of the design space that has been allocated to him with the design task assignment, the designer completes his design task.

3.8.6 Discussion and conclusion

The proposed cognitive model provides an explanation of design 'from the inside' i.e. a designer-centred view by detailing the cognitive activities performed during design. More specifically, the model explains how a designer draws on his personal knowledge (cognitive content) and expertise (routines) for design knowledge construction. If offers an explanation for the differences between designers, not only on the basis of the differences in design knowledge and expertise, but also with respect to other knowledge and expertise that they may activate for accomplishing their design task.

The model offers also an explanation about differences in elicitation (explicitness) of knowledge that varies from designer to designer and from design situation to design situation.

Finally, the model shows the role of methods and reference framework s (like reference architectures), the former as the source of routines for the designer, the latter as tools for structuring the design space.

4 A CASE STUDY

4.1 Case study: Loudspeaker design - Introduction

4.1.1 Purpose of the case

In order to illustrate the different concepts of the theory proposed in chapter 3, an integrated design case has been developed. Integrated means that the design project is described in all its aspects using the concepts proper to the respective contributions. The structure of the case follows the structure of the theory.
The case is not aimed at being complete: describing all (micro) events and activities (externally oriented or mental) that happen during a design project is impossible and would actually not serve the illustration purpose. Consequently, the case has been simplified and is theory-proving oriented; it can be seen as a verification and validation exercise for the theory in terms of realism and applicability of the concepts.

Attention has been paid to illustrate also the context wherein the design is taking place. Indeed, the context has a considerable impact on how the design process is implemented and on how the design activities are taking place.

4.1.2 Application of the theory to the case

The case study is presented with respect to the different parts of the theory with reference to the theoretical framework.

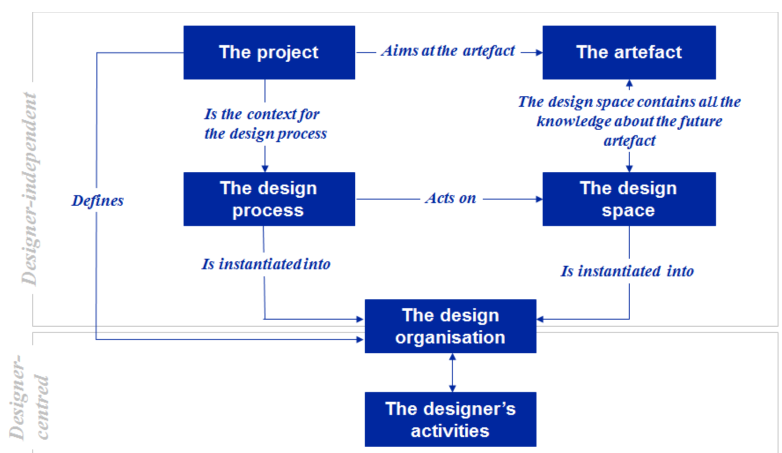

Figure 27: The theory framework as the guiding structure for the case study

- The project is initiated by the sponsor and leads to the (first) definition of the loudspeaker. In cases like this, the whole project covers the design and the realisation of the loudspeaker. Use is proper to the customer. Maintenance, when needed, is performed by the after-sales department. Hence, the project focuses on the design of the artefact without paying attention to other project phases and non-design activities.

4.2 Case study: The project

4.2.1 Project context

The SSE (Sound Systems Engineering) company is a recent (+- 7 years) and small company (less than 30 people) that is specialised in the design, construction and distribution of loudspeaker systems. They develop a range of loudspeakers (a product family) and sometimes develop speakers on special request. The main customers are people who attach a considerable importance to the sound quality of the loudspeaker systems.

For historical reasons, their strongest competency is in the design and the construction of loudspeaker enclosures. This is partially due to the background of management: mechanical engineers who are no too much acquainted with electronic engineering.

This is one of the reasons why they have developed a long term relation with two suppliers of components: drivers (speaker engines) and cross-over networks. The drivers are standardised, they form the offering of the suppliers. In exceptional case, suppliers may produce variants on request. The cross-over networks are developed upon the requirements of the customers, such as the SSE company, where the characteristics of the combination of drivers and loudspeaker enclosure and their interactions, are taken into account.

The company's organisation is simple:

- The general manager who started the company has also retained the design and engineering department.
- The sales and marketing department is in charge of sales and promotion of the company. It also watches the developments in the loudspeaker market.
- The production department is responsible for process planning, for the production facilities and the actual production.
- The after-sales department deals with the service to the distributors including transport, and manages the feedback received from distributors and customers.
- The finance and administration department is in charge of administration, accounting and financial planning and holds also the human resources responsibility.

From this organisation, resources (personnel and dedicated tools) are drawn so as to constitute on a continuous or temporarily basis for the organisation of the company's projects.

4.2.2 Definition of the overall project

The general manager of the company wants to renew and possibly expand the range of products. Therefore, he intends to launch a design project. If the design is considered promising, the next phase of

the project will consist of developing a prototype or several prototypes depending on the outcome of the first design phase. If the prototype is successful, production will be launched.
The general manager obviously wants a new loudspeaker to be specified but he has also in mind to give the design task to a young engineer who has recently been recruited in order to exploit the creativity of a person who possibly will bring in new ideas.

He has also other, non-communicated objectives: (a) to integrate in the company newly recruited engineers who will have to interact with a lot of staff, (b) to test the new engineers and (c) to confront the existing staff with the new ideas and new attitudes of the younger engineers and so introduce some change in the company.

For the general manager, the overall project, if carried out to the end, will consist of following phases: definition, preliminary design, prototyping, engineering design, and launch of production. For this case, only the preliminary design phase will be considered i.e. that part of the project where the designer will most actively be involved.

There are some accepted constraints (in principle, not negotiable): the long-term relations with the suppliers of speakers and cross-over networks will limit the number of drivers and driver combinations that will be considered.

4.2.3 Definition of the design phase

After an early definition of the project, where the general manager formulates for himself an idea of what the new loudspeaker should be, he decides for the project phasing as follows: preliminary design, prototyping, engineering design, and launch of production, if applicable. Hence, the first phase after the definition phase, that he performs himself, is the preliminary design phase.

The general manager may suggest to the designer a series of contacts by saying: “Go and have a talk with … (sales, production, after-sales, …)”. These are the stakeholders or their representatives (of the customers, suppliers and resellers). The designer may find out, during the design process that other people such as representatives of the suppliers or panels of potential client have to be involved and to be recognised as stakeholders as well.

The expected results of the design phase consist essentially of the specification of the loudspeaker with such a level of detail that a prototype may be realised.

4.3 Case study: The artefact

It should be noticed that, at the start of the project, the actual loudspeaker is not 'known' by the designer nor by anybody else. The general manager has a first idea he will be forward to the designer, as input. Hence, in this section, what will be described is:

- *Background information*: elements of loudspeaker engineering. In addition to provide some background for the reader, this can be understood as general knowledge that can be found in literature and that experts know. It is not sure that the young engineering knows this at the start of the project but progressively, he will learn from others and by searching.
- This *early definition* of the loudspeaker by the general manager.

4.3.1 'Common' knowledge about loudspeakers

What is described below is an arbitrary selection by the author of knowledge elements that is available about loudspeaker system engineering. It pertains to the notion of common knowledge shared by the community of loudspeaker designers.
It should be noticed that in the case, the knowledge about loudspeakers of the sponsor and of the designer may differ: there is no absolute and complete knowledge base that is available to anybody.

Working principles: the basic principle of a loudspeaker system is to transform electric energy provided by an amplifier that amplifies the signal of a source (CD player, DVD player, record player as well as the modern portable devices), into acoustic energy i.e. acoustic waves in the air in a listening room.

Loudspeaker components: there are a lot of exceptions, but a huge part of the loudspeaker systems use drivers (speakers engines) that consist of an elastically suspended membrane (often of conical form) driven by voice coil suspended inside a magnet and activated by the electrical current generated by the amplifier. The voice coil is attached to the loudspeaker membrane. Due to the limitations on the drivers, such as the capacity to handle with sufficient quality the full range of hear-able frequencies i.e. from typically 20 to 20.000 Hz, most loudspeakers aiming at a certain level of sound quality, use two or more drivers, one specialised in the higher frequencies with a good dispersion of the sound (that is frequency-dependent) but lower power handling and the other for the lower frequencies. For the lower frequency drivers, the size and the mass of the membrane are important as they determine the sound volume that can be generated for these frequencies; the lower resonance frequency determines the lowest frequency that can be produced by the driver.

Loudspeaker enclosure: there is a need to separate the energy projected forward and rearward by the driver, especially for the lower frequency driver since, at these frequencies, the driver is not directive; without a separating panel or an enclosure (a box), the rearward projected energy tends to neutralise the forward projected energy.

Enclosures can have different types of forms. The most common geometry is the parallelepiped i.e. with parallel panels; the panels being flat or curved.
There a structural issues with the enclosure: (a) internal form: parallel plat panels facilitate the creation of standing wavers which have an impact on the frequency response of the driver, (b) rigidity: panels with low rigidity tend to resonate at some frequencies. The sound generated by the enclosure 'colours" the sound emitted by the drivers: the composite sound wave emitted by the enclosure is distorted, (c) damping: any panel will resonate at some frequency but when it happens, it is important that the resonance ends rapidly; this is the role of damping characteristics of the material used for the enclosure.

Loudspeaker loading: there are different 'loading" modes of the bass driver i.e. ways to deal with the backward energy generated by the bass driver:

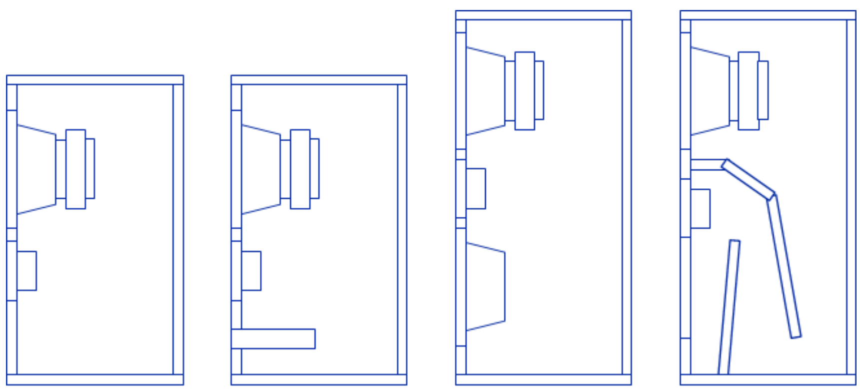

Figure 28: Variants of loudspeaker loading modes

- Closed enclosure: the energy is simply absorbed by damping material behind the diver, in a *closed enclosure*.
- Some of the energy is used to let the enclosure, with a hole in it and a pipe of definite length, to act as a Helmholz resonator that generates over a limited frequency range, a sound wave that complements the sound emitted by the bass driver. This is a *bass-reflex enclosure*.
- Enclosures with a *passive radiator* work along similar lines as the bass-reflex enclosure but the mass of air in the pipe is replaced by a loudspeaker without a magnet and whereby the mass of the membrane has the appropriated value.
- There are other loading modes (labyrinth or exponential horn). They are inherently more complex to design and to build. They are not considered for the case.

Cross-over network: in the simple case of an enclosure equipped with a bass-driver and a high frequency driver, the electrical energy is provided by the own amplifier of the customer. The enclosure is called passive as there is no specialised amplifier built-in in the enclosure. In such as case, there is need for a cross-over network that separates the frequency range over the different drivers: in the case of two drivers, one high frequency driver for frequencies typically above 3.000 Hz and a low frequency driver. The cross-over network can also help in equalising the frequency response of the overall system, taking into account the characteristics of the drivers in a given enclosure with a given loading mode.

Loudspeaker performance: important performance factors for loudspeaker systems are:

- Power handling: the capacity of the loudspeaker system to transform electric energy in sound volume.
- Bandwidth: the capacity to deal in an equal manner with the range of frequencies from 20 to 20.000 Hz. The range (lower and upper frequency limits of the loudspeaker system) and more specifically, the flatness of the frequency response are indicators for the 'neutrality' of the loudspeaker system.
- Transient response: as music and voice are highly variable sounds, the loudspeaker has to have a good transient response which means, a sound should be established swiftly i.e. as close as possible to the input signal and the loudspeaker should be sufficiently damped in such a way that the sound emitted by the loudspeaker system fades out as soon as the input signal from the amplifier ends.
- The level of distortion due to the non-linearity of the drivers, the colouration of the sound due to the enclosure, the non-neutral behaviour of the cross-over network, the acoustic interaction between the drivers, etc…

4.3.2 The initial definition of the loudspeaker

The initial definition is given by the general manager and is expressed in the property classes defined by the theory:

Type	• Traditional passive loudspeaker i.e. similar to the loudspeakers that can be found in the market	
Function	Identity related	• Self-image enhancer: the pleasure of the customer with an agreeable form (and a small size) and an exquisite sound reproduction. • The speakers should disappear in the mind of the listener so as to convey the full emotion of music. • When not in use, the speakers should have some appeal to the customer by its aesthetic properties or be barely visible.
	Relation related	• Gaining some additional prestige by owning and demonstrating to friends a high-quality and aesthetically

		pleasing or original loudspeaker
	Technology related	• High quality reproduction given the limited size of the loudspeaker • Number of drivers: 2, 3 in case of an enclosure with a passive radiator • Loading mode: closed, bass-reflex or passive radiator. No labyrinth enclosure considered too expensive to design and to build
	Target customers	• People interested in high quality music reproduction with a possible compromise on the limited bass response
	Target contexts	• Living room of limited size with modern furniture (rather reflexive) • Expected power of the available amplifier: < 80 Watt
Ergonomics		• Limited weight for reasons of manipulation by the user • Limited weight for reasons of transport
Embodiment		• 'Strong' backside panel for fixing the loudspeaker to a wall • Materials: traditional materials. Possibility to have different upper layers, to diversify the outlook of the loudspeaker. • Life-time: > 10 years
	Target interactions	• Sound reproduction (music and speech) from portable equipment, CD player via traditional power amplifiers. • Sound reproduction for home cinema

Table 5: The initial definition of the loudspeaker

4.3.3 Evolution of the definition and description of the loudspeaker

See the design space and the state transitions

4.4 Case study: The design space

4.4.1 The target content of the design space

The designer is asked to realise a complete design. Hence, the target content of the design space is the nominal content as defined in the theory. However, by instruction of the general manager, the anticipation of the life-time does not have to be fully detailed. Even if the designer may envisage temporarily different alternatives, he is requested to propose one loudspeaker. Temporarily, there may be as many instances of the artefact area in the design space as there are alternatives. In the end, there will be one area encompassing the description/specification of the proposed loudspeaker.

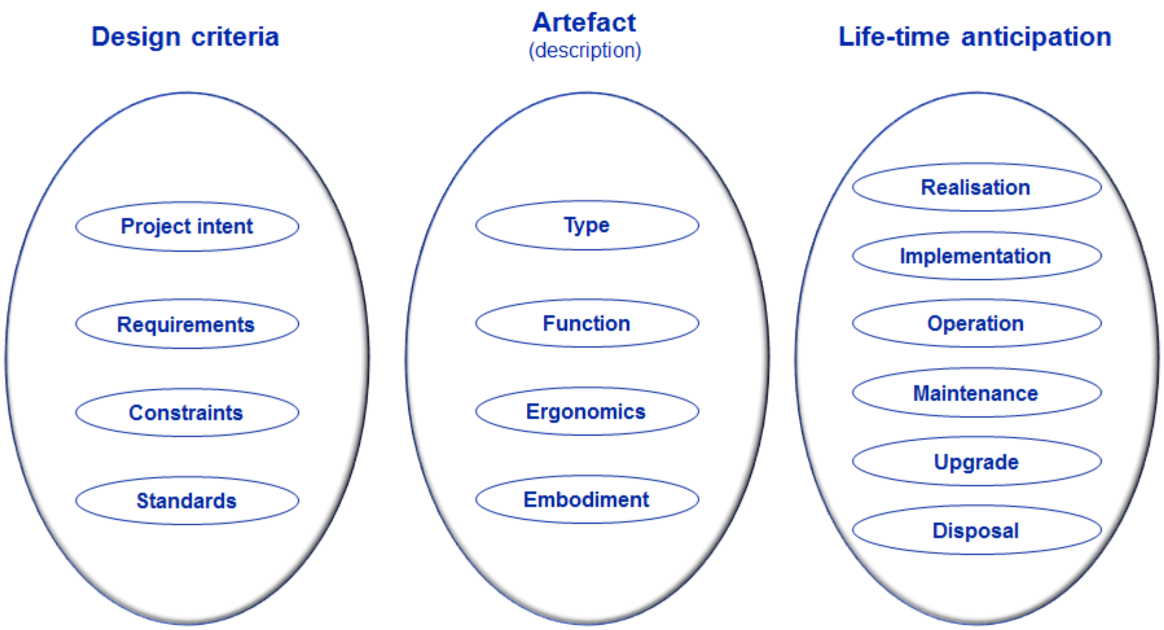

Figure 29: The content of the design space

4.4.2 The initial content of the design space (at the start of the process)

This content is derived from the input provided by the general manager.

Design criteria	Artefact (description)	Anticipation of life-time
Project intent • A small high quality loudspeaker for product line renewal	**Artefact type** • Closed enclosure, bass-reflex enclosure or passive radiator	**Realisation** • Utilisation of available manufacturing facilities
Requirements • Adequacy for pop and classical music	**Function** • Sound reproduction • Spoken word reproduction	**Implementation** • To be connected to amplifiers with a power range from 20 to

Design criteria	**Artefact** (description)	Anticipation of life-time
• To be specified		100 watt • Loudspeaker attached to the wall, on stand or on bookshelf • Normal living rooms • No over-damped rooms
Constraints • No labyrinth, nor exponential horn enclosures	**Ergonomics** • Not prohibitively heavy (for targeted customers)	**Operation** • (Nothing specific)
Standards • Company standards to be applied	**Embodiment** • Traditional materials (wood) • Finishing variants (colours, wood finish)	**Maintenance** • 90% of repairs to be done by re-seller
		Upgrade • Possibility to be foreseen to upgrade the loudspeaker with new components (drivers and cross-over network
		Disposal • Materials as recyclable as possible

Table 6: The content of the design space at the start of the design

4.4.3 The content of the design space at t_i (to be modified)

Changes are in italic

Design criteria	**Artefact** (description)	Anticipation of life-time
Project intent • A small high quality loudspeaker for *lower* product line renewal (one of the product ranges of the company)	**Artefact type** • Closed enclosure or bass-reflex enclosure • No passive radiator	**Realisation** • Utilisation of existing manufacturing tools • *Sub-contracting of enclosure panel to an external supplier for the first series production* • *Afterwards, insourcing* • *Acquisition of a new machine for making curved panels in layered material*
Requirements • Adequacy for pop and classical music • *Primarily aimed at reproducing classical music and easy listening music*	**Function** • Sound reproduction • Spoken word reproduction • *Music reproduction of small ensembles*	**Implementation** • To be connected to amplifiers with power range from 20 to 100 Watt • *Capacity of amplifier to handle low impedances: 2 Ohm min.*

Design criteria	Artefact (description)	Anticipation of life-time
• *Frequency range: 70-20000Hz ± 2db* • *Sensitivity: > 82 dB*		• Loudspeaker attached to the wall, on stand or on bookshelf • *Preferred installation: on bookshelf or attached to the wall* • Normal living rooms < *40 m²* • Not over-damped rooms
Constraints • No labyrinth, nor exponential horn enclosures • *Size max: 500*220*275mm³*	**Ergonomics** • *Weight < 10kg*	**Operation** • Nothing specific
Standards • Company standards to be applied	**Embodiment** • Traditional materials (wood) • *Layered enclosure panels: layers of wood and damping material (bitumen)* • *Finishing variants: wood (walnut and mahogany) & lacquer (5 variants)* • *Expected life-time: 15 years*	**Maintenance** • 90% of repairs to be done by re-seller
		Upgrade • *Possibility to be foreseen to upgrade the loudspeaker with new components (drivers and cross-over network) for evolution of the product line or for upgrade offered to the customers*
		Disposal • Materials as recyclable as possible

Table 7: The content of the design space at ti

4.4.4 State transitions of the design space

These transitions are described in the section on the design process as there are closely associated with the execution of the design process.

4.5 Case study: The design phase as design process instance

4.5.1 Definition of the design phase

The design process is the abstract process model as described in the theory and is being instantiated into the (preliminary) design phase.

4.5.2 Start-up of the design phase

In a kick-off meeting the general manager explains the design phase to be performed. He explains his views on: the context of the project (product range renewal and extension), the type of loudspeaker he has in mind, for instance, a two-way loudspeaker system consisting of a bas-medium driver and a high frequency driver and he adds some of the expected characteristics such as neutrality (lack of resonances of the loudspeaker enclosure) but also some geometrical constraints so as to limit the overall volume by the loudspeaker.

He provides a starting point for the design phase by referring to products developed in the past (as an example of what he has in mind and as a reference: "the new loudspeaker should be better than …"), to products of the competition the company has been able to acquire, to design documentation (the knowledge base of the company), to tools that may be used for drawing (a simple CAD Computer Aided Design Tools) as well as a library of computer routines that have been developed in the past for calculating characteristics of loudspeaker designs and finally, to company staff to be interviewed so as to provide input for the design.

He explains the typical duration of this preliminary design phase, the intermediate (progress) follow-up moments as well as the nature of the expected results:

- Requirements as part of the design criteria.
- Constraints (for example on weight, on complexity (a single enclosure as opposed to two enclosures) and on size).
- Design specification of the artefact that has been found as 'the best solution'.
- The justification of the decisions taken during design.

These results are expected to be written down in a design deliverable[18] (so as to contribute to the expansion of the knowledge base of the company).

[18] Deliverable means what-is-to-be-delivered or what is actually delivered. This is proper to the action of design planning, more specifically, planning the design result.

4.5.3 Design sub-processes

The design process consists of three main sub-processes: input appropriation, knowledge construction and output generation.

4.5.3.1 Input appropriation

Initial input

This sub-process includes the appropriation of the input provided by the general manager at the start of the design phase, input provided by the stakeholders and results of searches that the designer may undertake.

From the input of the general manager, it can be concluded that, in addition to design of an excellent loudspeaker, there are many different concerns among the stakeholders that have to be taken into account:

- The concern of the general manager: to make loudspeakers in a cheaper way, to try to conquer new markets, to increase profit and to foster growth.
- The concern of the marketing and sales manager: to develop a loudspeaker that is a differentiator in terms of sound quality or in terms of aesthetics as compared to the competition.
- The relation with the suppliers: maintaining good relations and when necessary, to push them to improve the quality of the drivers that will be acquired by the SSE company.
- The concern of the production manager: the design must use some material that resist better to shock and find a way to allow better fixture of some components during manufacturing
- The concern of the logistics manager: in view of the rate of damage during transport and delivery, to have more robust loudspeakers than in the past.
- The concern of the after-sales manager: to design loudspeakers easier to repair and to avoid using components prone to failure.

It is up to designer to elicit from the above (and from additional interviews) the requirements that will act as (a part of the) design criteria for evaluating the candidate artefacts.

Additional input and search

Since the designer has no direct contact with current and future users, he starts gathering information from the people that must know these requirements: the sales manager, other designers who have designed in the past loudspeakers of the same type, the production department, the after-sales responsible who can brief him on the problems encountered by customers and on the needs they formulate when communicating with the company about these problems. Unless the designer is highly directive as to the subject of the interviews (for example, on focusing uniquely on requirements), he will gather a lot of information that pertains to the different design areas of the design space and that has to be sorted out and made consistent. Incompleteness or inconsistency may require additional interviews or search in the knowledge base of the company or in any other source.

The information gathered is typically:

Type of event	Knowledge acquired
Interview with sales	• Performance requirements for sets of products and for this particular type • Requirements on aesthetics • Constraints on size and weight • Constraints on costs (related to pricing and profit margin) • Suggestions for artefacts for completing the product range and beating the competition • Suggestions on the subset of drivers to be acquired from one of the suppliers
Interviews with (other) designers	• Suggestions as to revolutionary types of loudspeakers • Requirement-types and examples • Key issues to be addressed (prioritising the areas to be completed in the design space) • Suggestions for types of artefact structure, for materials and material combinations • Suggestions of drivers and cross-over networks to be used, either actually or as a starting point for the design
Interview with the production manager	• Constraints associated with realisation (artefact complexity, types of materials, capabilities of the machines) given the available capabilities • Suggestions on the artefact structure
Interview with the after-sales manager	• Suggestions on packaging • Performance and other requirements • Feedback on structural quality of the enclosures and the durability of the drivers of existing products
Interview with the general manager	• Weighting the different requirements and constraints, for example by categorising the requirements in: MUST, WISHED and NICE TO HAVE categories

Table 8: Information gathered from interviews

4.5.3.2 Knowledge construction: transitions in the design space

The content of the design space evolves and is enriched progressively by execution of the design process. The process involves numerous events whereby the designer enriches or modifies the content of the design space. These events lead to iterations (on the content of the design space), where each iteration corresponds to any change of an element, of a cluster of elements or of the relation between elements.

Alternative approaches for executing the design process

Dealing with the design space areas can be done at random; the theory does not prescribe a given sequence, provided that at the end of the design task the different areas of the design space are (sufficiently) consistent and that the entities are consistent with each other.

If the designer does not use a method he has appropriated (learnt) in the past, he can use one of the following approaches:

1. Filling the respective areas with knowledge derived from the inputs and completing the respective areas at random, on the basis of his personal knowledge and of information he gathers from the stakeholders. This approach involves the risk of divergence (or at least not converging in due time) due to the huge number of iterations.
2. Addressing first the design criteria areas in the design space: the project intent, the requirements, the constraints and the applicable norms and standard. This would require a series of activities of information gathering in documents and by interviewing the different stakeholders. Thereafter, he would try to invent one or more alternative loudspeakers, with their type, functional aspects and embodiment. He would then proceed to the validation of the different alternatives using the design criteria. He may then devote some time to anticipate the realisation of the loudspeaker. This leads normally to changes in the embodiment of the artefact or even to the addition of a new requirement. It should be noted that requirements are not necessarily a good source of inspiration for novel designs.
3. Formulating work hypotheses: the designer may include, at the beginning of the design phase, an exploration step, using for instance past designs that seem to correspond to the project at hand. On this basis, he may tentatively fill in the different areas of the design space with tentative content (hypotheses). The work to be done thereafter is to verify, modify and expand those hypotheses with input from the stakeholders so as to define the exact requirements and by applying variations on the artefact that has been taken as a starting point. The advantage of this approach is that the designer is better prepared before the contacts with the stakeholders. The danger is not to be able to deviate from the preconceived ideas developed in the exploration step.
4. Inventing an innovative loudspeaker or a set of loudspeakers, by assembling and improving the best ideas of the company and of the competition and to bend them so as to comply with the requirements of the stakeholders. This approach presents the benefits of possibly changing traditional views of the stakeholders and to lead them to more innovative concepts. Such an approach is often followed by senior designers but may prove too difficult for a junior designer.

This is illustrated with a few iterations that show the evolution of the two of the areas in the design space: requirements as a sub-area of the area: design criteria) and artefact.

Iteration	**Design criteria** (requirements)	**Artefact**
	State i	
i	R1. Use of existing production tools R2. Small loudspeaker R3. Applicable for all types of music (classical and pop music) R4. To be used on loudspeaker stand, on bookshelf or attached to a wall R5. Frequency response: 40 – 20.000 Hz +-2db R6. Sound volume produced by enclosure panels: -10 dB at all frequencies R7. Sensitivity (as a measure of sound volume to be produced): > 85 dB R8. Sound quality: better than model NN (previous model of the SSE company or competition)	A1. Traditional box: parallelepiped A2. Loading modes: closed, bass reflex, passive radiator. NO labyrinth A3. Panel material + damping layer A4. Drivers: Supplier 1 Model B3 +Model M 2 Model T6 A5. Cross-over: derived from Supplier 1 CO 326
	Transition	
Changes further to the intermediate validation	• *The designer refines the notion of 'small'. It becomes a quantitative requirement (or constraint)* • *The designer comes to the conclusion that the required frequency range is impossible to achieve, given the need for a small loudspeaker. This requirement is relaxed to 60 – 20.000 Hz.*	• *After a series of calculations, the labyrinth loading mode is not retained any more for following reasons: the volume necessitated by a labyrinth enclosure to reach 40 Hz, the required flatness of the frequency range and the need to tune the labyrinth perfectly to the resonance frequency of the bass driver while the variation of the characteristics of the bass driver is +-10%* • *The three-way alternative is rejected for reasons of cost and because it is difficult to calculate precisely the right cross-over network and the lack of calculation capacity would necessitate excessive testing effort so as to optimise the loudspeaker* • *There is also a change in candidate bass driver so as to increase sensitivity.*
	State i+1	
i+1	R1. Total volume of the enclosure: < 50 dm³ R2. Applicable for all types of music (classical and pop music) R3. To be used on loudspeaker stand, on	A1. Traditional box: parallelepiped A2. Loading modes: closed or bass reflex A3. Panel material + damping layer or high density material (plaster stone covered by a layer of fine wood) or dual panel with sand between these panels (as damping

Iteration	Design criteria (requirements)	Artefact
	bookshelf or attached to a wall R4. Frequency response: 60 – 20.000 Hz +- 2db R5. Sound volume produced by enclosure panels: -10 dB at all frequencies R6. Sensitivity (as a measure of sound volume to be produced): > 85 dB R7. Sound quality: better than model NN (previous model of the SSE company or competition)	material) A4. Drivers: Supplier 1 Model B3b + Model T6 A5. Cross-over: derived from supplier's model: 1 CO 36g
	Transition	
Changes further to the intermediate validation	• *The maximum size of the enclosure is further reduced* • *In view of the alternatives in mind, it appears impossible with the constrained size and the available drivers to reach the goals of frequency range and flatness*	• *Hence, a discussion starts and concludes by the exploration of two main alternatives. T1: a closed enclosure with a flat frequency range but further limited to 75 Hz and aimed at a more narrow audience of amateurs of classical music* • *T2: a bass reflex enclosure with a more fluctuating frequency response (+- 3.5 b) but extending to 50 Hz* • *The same drivers will be used (idea of product family)* • *The cross-over networks will differ*
	State i+2	
i+2	Type 1 (alternative 1) R1. Total volume of the enclosure: < 30 dm³ R2. Applicable for classical music R3. To be used on bookshelf or attached to a wall (so as to improve the bass response by wall reflection) R4. Frequency response: 70 – 20.000 Hz +- 2db R5. Sound volume produced by enclosure panels: -10 dB at all frequencies R6. Sensitivity (as a measure of sound volume to be produced): > 85 dB R7. Sound quality: better than model NN (previous model of the SSE company or competition)	Type 1 (alternative 1) A1. Traditional box: parallelepiped A2. Loading mode: closed A3. Panel material + damping layer or high density material (plaster stone covered by a layer of fine wood). The dual panel with sand between these panels (as damping material) is excluded for reasons of weight A4. Drivers: Supplier 1 Model B3b + Model T6 A5. Cross-over: derived from Supplier 1 CO 36g
	Type 2 (alternative 2) R1. Total volume of the enclosure: < 30	Type 2 (alternative 2) A1. Traditional box: parallelepiped

Iteration	**Design criteria** (requirements)	Artefact
	dm³ R2. Applicable for pop music R3. To be used on loudspeaker stand, on bookshelf or attached to a wall (so as to improve the bass response by wall reflection) R4. Frequency response: 70 – 20.000 Hz +- 3.5 dB R5. Sound volume produced by enclosure panels: -10 dB at all frequencies R6. Sensitivity (as a measure of sound volume to be produced): > 88 dB R7. Sound quality: better than model NN (previous model of the SSE company or competition)	A2. Loading mode: bass-reflex A3. Panel material + damping layer or high density material (plaster stone covered by a layer of fine wood). A4. Drivers: Supplier 1 Model B3b + Model T6 A5. Cross-over: derived from Supplier 1 CO 36br
	Transition	
Changes further to the intermediate validation		• *From now on the design concentrates on the type of materials to be used. Instead of complex panels, the choice is made to use panels consisting of two layers of MDF (Medium Density Fibre) material for rigidity separated by a layer of bitumen for damping.* • *Lead, envisaged as a potential damping layer is not retained in view of the excessive weight.* • *Both types of loudspeakers are aimed to be built with the same type of panels.* • *These panels can be produced by the existing machines.* • *More elaborate multi-layers panels offering better neutrality (lack of resonance), if adopted, should be outsources at least on a temporary basis until the company has the machines and the competences to produce them.*
	State i+n	
i+n	Lately introduced constraint during one of the discussion with the after sales manager, in relation to the cost of transport: Weight < 15 kg	• Drawings are prepared so as to allow geometric verification (can the drivers be correctly mounted on the front panel?) • On the basis of the drawings, the selection of the drivers and the type of panels to be used, calculations of weight can be made so as verify that the weight complies with the constraint.

Table 9: Design space states and transitions

Notes

1. Rx stands for requirement. Ax stands for (artefact) attribute.
2. The requirement *R1. Use of existing production tools* is dropped in the later states of the design space: it has been considered in the initial design steps but it is dropped as it can be interpreted as a constraint pertaining to the design space area 'life-time anticipation' which is not analysed in the present case study.

4.5.3.3 Output generation

Depending on the agreed planning, work-in-progress material (intermediate reports) may be developed for discussion at intermediate milestones.
The final output (the design report), submitted at the end of the design, has to be complete in regard to the wishes that the general manager has expressed. It may also contain additional relevant material provided by the designer.

<u>The design output (table of contents of the design report)</u>

1 Introduction
1.1 Reference to the mission statement given by the general manager
1.2 Definition of the project
2 Requirements, constraints and applicable norms and standards
2.1 Requirements as derived from the needs and expectations of the customer representatives
2.2 Constraints and standards as learnt from people contacted during the design process
3 Specification
3.1 The type of loudspeaker: types envisaged and actually chosen + justification
3.2 <u>Function</u>
3.2.1 Type of users targeted at
3.2.2 Type of music material to be reproduced
3.3 <u>Ergonomics</u>
3.3.1 Size
3.3.2 Weight
3.4 <u>Embodiment</u>
3.4.1 Expected life-time
3.4.2 Layout and structure
3.4.3 Work-breakdown structure
3.4.4 Specification of components
3.4.4.1 Drivers
3.4.4.2 Cross-over network
3.4.4.3 Panels

3.4.4.4 Internal reinforcements

3.4.4.5 Finishing layers

4 Realisation

4.1 Specific aspects of realisation

4.2 New machine to be acquired

4.3 Temporary sub-contracting

4.4 Capabilities to be developed (training)

5 Implementation and operation

5.1 Target power amplification

5.2 Typical room

6 Life-time considerations

6.1 Maintenance and upgrade

6.2 Disposal

7 Conclusion

7.1 Recommendation for the next phase: prototype development

7.2 Considerations on marketing

7.2.1 Initial market volume estimate

7.2.2 Early suggestions for marketing (enclosure characteristics to insist on)

7.2.3 Initial estimate of cost

8 Appendix

8.1 Detailed design material

8.2 Rationale and justification of design decisions

4.5.3.4 Termination of the design process

For the designer, the design process ends when the design space is sufficiently completed and sufficiently consistent based on his personal (objective and subjective) criteria. The design report should allow the general manager getting the feeling that the design has been completed, for instance, in terms of number of alternatives studied or in terms of level of innovation as compared to existing products. Before final validation and acceptance of the design results, the general manager may decide to have a peer review of the results by other designers of the company.

4.6 Case study: The design organisation

4.6.1 The design organisation

The set of people allocated to the design phase is organised as follows:

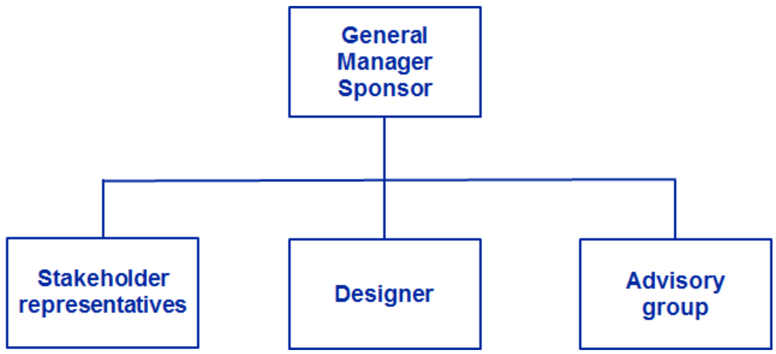

Figure 30: The structure of the design organisation

This organisation results from decisions made by the general manager. He retains the overall project management accountability, letting the designer to concentrate on design activities. He has authority over the stakeholder representatives who will act as information sources for the designer. He wants also an independent advisory group that will review the design proposal and make recommendations to him.

4.6.2 Decomposition of the design phase into tasks

The design process (the abstract model) is instantiated into the design phase. The latter is decomposed in tasks that are in line with the design sub-processes (input appropriation, knowledge construction and design expression).

All these sub-processes form the design task to be performed by the designer himself except two:

- Input generation by the stakeholder representatives (in so far that they are proactive)
- Assessing the design, done by the advisory group.

4.6.3 Task allocation

Accordingly, the task allocation of the design phase is:

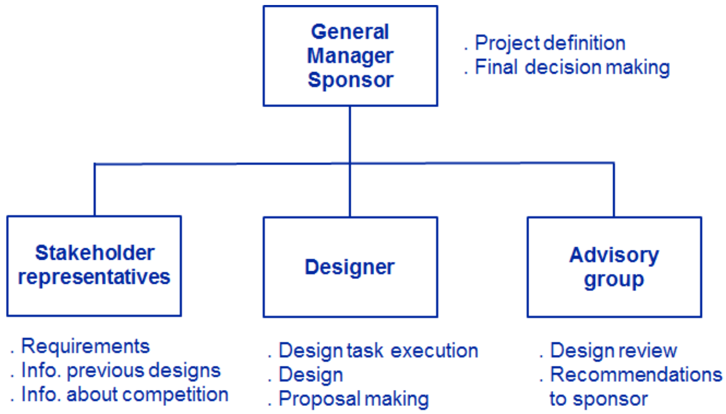

Figure 31: Task allocation in the design organisation

4.6.4 Task appropriation

The designer has to appropriate the design task, not only by understanding the task but also by committing to it. Depending on his personal ambitions, he may be motivated to explore creatively alternatives that were not originally envisaged by the general manager and try to relax some constraints in order to widen the range of alternatives. This means that the design intent (driving the design activities) may differ as compared to what is derived from the project intent as defined by the general manager.

In the present case, he may deviate, for reasons of personal interest and ambition, as compared to the initial definition of the loudspeaker and explore the labyrinth loading mode with a sophisticated labyrinth (a special kind of pipe built inside to enclosure) which might extend the lower frequency range of the loudspeaker well beyond the range that might be expected from a small loudspeaker.

4.7 Case study: The designer's activities

During the design, the designer deploys a series of activities of interaction with people, with existing artefacts, with information sources documents and knowledge bases) and with tools. Here we focus on the cognitive activities of the designer.

It has to be noticed that this is a simplification (in terms of volume and in terms of detail) of the mental processes in the sense that the conscious processes cannot be expressed with all their detail, due their volume and their volatility. By definition, the designer is not even aware of the processes that are unconscious and that nevertheless contribute to the design. Hence, what is described is a fraction of the actual mental processes and elements manipulated during design. For the sake of simplification, the description is further focused on the requirements (a part of the design criteria) and on the artefact: these subjects are quite different by nature. Nevertheless, strong links exist between them. The illustration in representative because, for all entities in de design space, the three processes: activation, transformation and evaluation are applicable. They differ of course by the specific routine that is activated so as to instantiate them.

4.7.1 The designer's cognitive resources

The designer's cognitive resources consist of the knowledge (cognitive content) and experience (routines) he has acquired during education and during his professional activities. In fact, the designer has his whole life-time knowledge and experience as cognitive resources; if he wants to innovate he can try to activate content and routines that are well beyond his domain of professional expertise.

4.7.2 Task initialisation

Officially, the designer's task starts with the general manager assigning the task to the designer. The actual cognitive activities may have started earlier for example, with the designer already reflecting, on his own, about developing a small high-quality loudspeaker.

In any case, the discussion with the general manager and the appropriation of the input provided by him, leads to the initialisation of the working memory (short-term memory) with content associated (for the designer) with the notion of loudspeaker.

4.7.3 Core cognitive processes

4.7.3.1 Activating content in the working (short- term) memory

The working memory is enriched on the basis of the available cognitive content and by triggering routines to activate content (cognitive elements), transforming the content and evaluating the content. Unless the designer has a routine for it[19], most frequently, the enrichment of the design space occurs at random. All

[19] This would be the case if the designer has repeatedly applied the same method in several cases of loudspeaker design and if he has developed 'design habits' or an personal method.

types of content and constructs can be involved: content pertaining to perception through the five senses, discourse elements (words, phases), abstract schemata such as abstract models, concepts, physical laws, theories…. In other words, the cognitive content in the working memory is not limited to concepts[20] that can be represented by a word.

Activating content about requirements

Activation routines	Constructs in the working memory
Activation further to the interaction with people • The designer interacts with people and asks them what should be the requirements for a new loudspeaker. The designer asks which type of loudspeaker would beat the competition	• Initial requirements to be refined. For instance, a requirement such as high quality will have to be detailed in terms of: frequency range, flatness of the frequency response, power handling capacity etc… • General characteristics to be decomposed in specific requirements
Activation further to the interaction with information sources • The designer investigates the knowledge base of the company and discovers classes of requirements that have been defined for previous loudspeakers	• Potential requirement types to be made more specific for the design at hand. • In addition, the designer will have to check whether all these requirements types are applicable to his specific design.
Free-wheeling (alone) and brainstorming (with other people) • The designer remembers loudspeakers he has seen and listened to and wonders how to translate the global characteristics in specific requirements • The designer remembers reactions of people in observed situations where loudspeakers were listened to or discussed about Systematic loudspeaker-type analysis on the basis of loudspeakers at hand or described in literature • Analysis of the characteristic common and specific to different types	• Global requirements, for instance, on sound quality ('a pleasant sound') or on aesthetics ('a nice loudspeaker') that may be not translate-able into specific requirements and yet have to be taken into account. • Rationale(s) about requirements, for instance, on the basis of the questions: 'What is a loudspeaker? What are the operating principles? What is its function of the loudspeaker?'

Table 10 : Activating content about requirements

Some requirements may remain tacit i.e. the people involved know them but do not spend time in formulating or discussing them. For instance, the dispersion of sound that is frequency-dependent is important. It is the capacity of a loudspeaker to radiate the sound evenly in all directions. This depends, among other factors, on the size of the membrane of the driver. The corresponding requirement may

[20] An example of the image of a mother with a child that in one situation may refer to the family of the designer and in another situation may refer to the notion of 'care'. Another example is the picture that of a trumpet that for a while, stands for a loud and hard (with a lot of over-tones) sound.

remain tacit because all the people involved feel that for the design at hand, the drivers that may be used are good enough where dispersion is concerned.

Activating content about the artefact

The content is activated by all kinds of triggers: by evoking the words associated with loudspeakers (speaker, enclosure, driver, cross-over network, neutral, frequency response, hollow sound, resonance, …), by evoking episodes experienced in the past and by association with other episodes, by evoking affects experienced at the occasion of these episodes and by association with similar or opposed (like vs. dislike, feeling of success vs. feeling of failure) affects experienced in other episodes, by evoking rationales, theoretical models and theories known about loudspeakers and associated artefacts. The activation routines may be systematic or more intuitive (by unconscious association of cognitive content).

The above is direct activation. Indirect activation occurs during the interactions of the designer with other people in various contexts, with artefacts and tools.

Activation routines	**Constructs in the working memory**
Activating loudspeaker (or associated artefacts)-related episodes • Episodes of listening to loudspeakers • Episodes of perceiving loudspeakers in shops or bars • Episodes of installing and manipulating loudspeakers • Watching loudspeaker production and handling e.g. packing for transport • Episodes of deep inspection of loudspeakers for understanding how they have been made resp. conceived and how they work	• Alternative loudspeakers by form and by size • Components of artefacts: structure of panels • Positioning drivers each to each other • Alternative internal structures of loudspeakers for loading or for structural reinforcements (bracing) so as to increase the rigidity • Alternative materials for loudspeaker panels and for damping • Driver layout • Colours, sizes, forms…..
Activating structured cognition about loudspeakers and associated artefacts • Personal typologies developed on the basis of personal knowledge and experience • Rationales about loudspeakers e.g. key issues in loudspeaker design • Theoretical models of loudspeakers • Partial or comprehensive theories about loudspeakers	• Specific rationales (for this specific design process) linking loudspeakers properties with performance characteristics (for instance, if the size of a panel increases, its rigidity will decrease and there will be a need to increase the thickness of the panel or to change the panel material) • ….

Activation routines	Constructs in the working memory
Activating episodes and structured cognition about other artefacts • The designer remembers other artefact types he interacted with and wonders whether some characteristics might be applicable to loudspeakers	• Free-wheeling: 'can a balloon filled with gas, driving by a musical signal and accordingly expanding and shrinking, act as a transformer of electric in acoustic energy'[21]

Table 11: Activating content about the artefact

4.7.3.2 Transforming content in the working (short-term) memory

Transforming content about requirements

Activation routines	Constructs in the working memory
• Listing (and completing)	• The designer lists all the requirements he records during the different interactions with people as well as with information sources (for instance, with previous design files where he gets ideas about potential requirements that were not yet formulated)
• Ordering	• The designer classifies the requirements per nature • Functional requirements: performance • Embodiment requirements • Requirements derived from the anticipated realisation • Requirements derived from the anticipated artefact life cycle
• Decomposition	• The designer decomposes an overall requirement for instance on aesthetics in aesthetic requirements on: • Form • Colour • Materials
• Composition	• Association of requirements that still keep their individual character in structured sets
• Weighting	• Giving a relative weight to the requirements
• Integrating	• Combining several requirements into a new one that replaces them

Table 12: Transforming content about the requirements

Transforming content about the artefact

The designer may choose among different routines he knows so as to transform the contents of the entity: artefact

[21] During free-wheeling some 'crazy' ideas may come to the mind of the designer and sometimes lead to innovative concepts

Transformation routines	Constructs in the working memory
• Variation	• The designer starts from a main idea of loudspeaker and varies the characteristics such as size, the drivers, the type of loading, the internal structure. Hence, he generates a series of versions of the initial artefact.
• Classification	• The designer identifies the main parameters of a loudspeaker and classifies alternatives coming to his mind in a tree structure • He may also extend the tree by examining the possible combinations: (size*drivers*loading* internal structure*…) and retain the most promising combinations
• Decomposition	• The designer decomposes one or more artefacts in components and component-types. This corresponds to trying to find an answer about what are the key elements in the design.
• Composition	• The designer uses basic components to assemble candidate artefacts (without building a comprehensive tree of alternatives) • Composition pre-supposes an earlier activity of decomposition or the availability of standard components or combinations of components • The designer tries to characterise a candidate artefact as a specific combination of components.
• Rationale construction	• The design establishes a relationship between characteristics of the loudspeaker.
• Integration	• Integration is similar to composition with a strong focus on consistency. During integration, conflicts may appear such as the internal volume needs for a driver loaded as a bass-reflex conflicting with the requirement of a small enclosure or the constraint on the volume.

Table 13: Transforming content about the artefact

The above routines are examples of the transformation routines that are proper to the specific designer. Their nature and their level of elicitation (explicitness) differ from one designer to another. The designer may have alternative routines for a cognitive process and use one of them, depending on the context.

4.7.3.3 Evaluating content in the working (short-term) memory

Most frequently, evaluation involves comparison of one entity (for example, an imagined artefact) with another. Whenever the comparison is somewhat refined, criteria come into play. These criteria can be explicit but they can also be implicit and based on the intuition of the designer. This intuition is grounded in the designer’s knowledge and experience. Implicit criteria are not elicited for the reason that elicitation involves a certain cognitive cost (mental effort) as compared with the benefit of a potentially better evaluation using elicited criteria.

Evaluating the requirements

Evaluation routines	Constructs in the working memory
• Weighting or prioritising requirements	• The designer, when facing a long list of requirements may, alone or in collaboration with others, give a different weight to the different requirements • He may then focus primarily on the most important requirements and at the end of the design, verify that the design copes also with the less important requirements. If not, he may decide to drop the requirements that cannot be complied with[22].
• Validating requirements	• The designer verifies the requirements on the basis of the state-of-the-art (other loudspeakers at hand or described in literature) • He assesses the feasibility and he has to decide about the level of ambition for the loudspeaker being designed: within, equal to or better than the state of the art

Table 14: Evaluating the requirements

Evaluating the artefact

Evaluation routines	Constructs in the working memory
• Evaluating completion	• The designer verifies, by comparison with known loudspeakers, that this one is complete and that all aspects have been addressed so as to allow realisation, in other words, that the specifications are complete
• Evaluating consistency	• The designer verifies that the different components of the loudspeaker fit together. Special attention is given to the interfaces between components • Inconsistencies may emerge during this evaluation. Some of the inconsistencies will be resolved by activating additional cognition and by further transformation of the constructs of the design space. Inconsistencies can be persistent: the design will have to enter a problem solving activity that will question the options made so far and, if the design does not reach a solution, the definition and the hypotheses at the basis of the design task may have to be questioned. • During the design, the designer can tolerate inconsistencies for a while in order not too hastily reject a design alternative

[22] There is a philosophical question about requirements: should the requirements be fully complied with or are they goals that have to be reached as closely as possible? Similarly, can some requirements be dropped or not? In commissioned design, this is a matter of discussion with the sponsor and the other stakeholders.

Evaluation routines	Constructs in the working memory
• Evaluating alternatives	• If different alternatives emerge during the design, the evaluation will involve the use of criteria (explicit or implicit as stated above)

• Evaluation of the artefact against the requirements	• This evaluation assessed the properties of the future artefact with the set of requirements that have been defined (and validated). Most frequently, there are m requirements and n properties.
	• The mapping (the evaluation of the artefacts properties with the requirements) may trigger
	  • A feedback on the artefact: further enrichment and transformation of the design space to adjust the artefact
	  • A feedback on the requirements in terms of structure (decomposition of requirements) or in terms of level of ambition
	  • A feedback on the evaluation routine (the use of another method for mapping the artefact properties with the requirements)

• Evaluating the artefact on the basis of design standards	• Is similar to the evaluation of the artefact against the requirements
• Evaluating the artefact on the basis of personal criteria	• The designer may use personal criteria such as aesthetic ones, not necessarily relating the form of the artefact but to the simplicity and the elegance of the design[23]

Table 15: Evaluating the artefact

4.7.4 Exception handling

An example of exception situations (problems) the designer may encounter is the positioning within the enclosure of the cross-over network. It is on a printed board of standard size. Due to the internal dimensions of the enclosure, there are a limited number of places were the cross-over can be fixed but some positions may be too close to the magnet of the bass speaker, creating the risk of interference between cross-over coils and of the magnetic field of the loudspeaker driver.

After proper examination of the problem, the designer comes to several alternative solutions: (a) increasing some of the dimensions of the enclosure, (b) changing the inside proportions and even the form of the enclosure so that more space becomes available for the printed board, (c) discussing with the printed board provider for changing its dimensions or, (d) using another speaker that has not external magnetic field. Any of the alternatives has an impact on the design (maybe to be partially redone), on the aesthetics, on the performance and on the cost of the loudspeaker.

[23] By using such an aesthetic requirement, the designer can reject all previous alternatives and come to an elegant enclosure design: a flat panel for fixing the drivers, the left, rear and right panel made of a curved panel in multiplex (two layers separated by a layer of bitumen for damping) and a top and lower panel connected with a bar under stress so as to eliminate residual resonances.

In terms of cognitive activities, the designer then enters a cognitive task of another type: exception handling (problem solving). The entity ‘problem’ is analysed and cognitive content is added (the problem is described, for example, in terms of additional requirements and constraints).Variants of the artefact are generated (with the modifications envisioned) and the variants are evaluated (compared each to each other) or against a series of criteria. Part of the problem solving process may be unconscious such as in the situation where the designer goes to bed with a haunting problem and discovers, the next morning, that he has found the solution.

4.7.5 Consolidation process: learning

The consolidation process of working memory content into long-term memory content is a learning process. There are two types of learning:

- *Content learning*: the expansion of the designer’s knowledge happens by simply performing design. In the future, he will remember, at least partially, the design of the present loudspeaker. Learning can be unconscious or it can be guided, either under the control of the designer who records the main topics he has learnt and experienced during this project, or mediated by somebody else (a senior designer acting as a coach) by discussing and identifying the lessons learnt.
- *Routine learning*: similarly, routine or capability development occurs unconsciously, by doing, or more explicitly, by developing a framework (for example, a checklist) that may guide the designer during a next project.

4.7.6 Termination of the designer’s activities

The cognitive activities may be terminated with the formal end of the design phase. However, it is quite probable that the designer will go on with reflecting on the loudspeaker and still try to find a better one.

4.8 Case study: Findings and Conclusions

4.8.1 Findings

4.8.1.1 Illustration of the different contributions to the theory

The case has illustrated the main concepts of the theory with the project as the context of design, the loudspeaker as the object of design, the design space as the conceptual space where knowledge about the loudspeaker is building up further to the design process and sub-processes, the design organisation and the designer-in-action via the description of his cognitive activities. This illustration has been done for a case that is quite acceptable in terms of realism.

A case is by nature limited, the present one showing a design organisation that is mainly a mono-designer situation whereby the stakeholders act as information sources and the advisory group as the set of people doing a final assessment of the design. But is appears to be sufficient for its purpose.

On the other hand, the expression of the case is naturally limited. Indeed, documenting all details of the processes, including the mental ones, and of the contents of the design space and its transitions, would generate a huge volume of material well beyond the purpose of the case.

4.8.2 Conclusions

The case illustrates the benefit to consider, in design, all function dimensions of the artefact at the same time. The designer is not only in charge to deal with the technical function. In such a case, one may consider that the marketing and sales department is in charge of the 'aesthetics' and the 'image' associated with the new product. This often leads to a lot of iterations between the marketing and sales department and design, until an acceptable compromise is found.
Being aware of the three function dimensions allows the designer to raise, during the interviews, more precise and relevant questions to the marketing and sales department. He has to be aware that the technical dimension is not sufficient to ensure the success of a product; the loudspeaker has to be embedded in an economic, social and cultural context.

The case shows also that there is a degree of freedom or flexibility between the design task as allocated by the general manager and the design task as performed by the designer. Depending on the designer's ambition, interest and competence, he may innovate and propose one or even more loudspeaker models that were not originally envisaged by the general manager and that present higher levels of performance or commercial success.

Finally, the designer designs with all his personality and not only with the design knowledge and experience he has acquired during previous projects. He may explore other types of knowledge and experience so as to innovate.

4.9 Case study: References

There is a huge literature about the theory and practice of loudspeaker engineering. Accessible and synthetic books on the subjects are listed below. Although some are aimed at amateur-designers, they are known to be used by professional loudspeaker builders. The level of sophistication of the information sources and the technologies applied may be more developed in big forms.

[Colloms-1980] High performance loudspeakers (Second Edition). Colloms M. Pentech Press Limited; London. 1980

[Dickason-1999] The loudspeaker design cookbook. Dickason Vance. Audio Amateur Press (Fifth Edition)

[Hiraga-1980] Les haut-parleurs. Hiraga J. Editions Fréquences. 1980.

[Klinger-1989] Klinger H.H. Lautsprecher – Baubuch für HiFi Amateure und Musik Freunde. Franzis-Verlag Gmbh. München.1989.

5 FINDINGS, CONCLUSIONS AND PERSPECTIVES

This chapter is divided in three sections: (1) the findings relating to the theory in its present form and to its development, (2) the conclusions that can be drawn from the theory as it is and (3) the perspectives for further development.

5.1 Findings

The main elements of the theory can be summarised as follows.

First, the theory proposes a framework for describing and analysing design. This framework identifies several key themes in the theory. By handling them in a semi-independent way, it is possible to focus selectively on one of the themes. The framework also reduces the complexity of dealing with design as whole.

Second, the framework acts also as the articulation for several essential theoretical contributions:

- The project as the context for the design process: the design process is situated in its context and this allows proposing a definition of design that is related to its purpose: design is a knowledge construction activity aimed at reducing the uncertainty for the later phases of the project and of the life-cycle of the artefact.
- The design space comprising all the knowledge that is being built up during the course of the design activities. The theory proposes a nominal target content so as to cover all the areas where knowledge construction is required but acknowledges that there may be variations as to the target content depending on the particular project and for reasons of partial elicitation of knowledge. This relates to the various design phases found in methods (conceptual, preliminary, functional, technical, or detailed design) as well as to the level of explicitness of knowledge during the design process.
- The design process constructs knowledge in the design space, in the respective areas. There is not a priori sequence of activities. There may be logical dependencies between the design criteria, the knowledge of the artefact and the anticipation of realisation and the further life-cycle of the artefact but these dependencies can be bypassed by hypotheses considered a tentative content. The actual structure of the design process will depend not only on the design organisation and on the applied methods and routines but also on the knowledge that is available at the start of the process.
- The design organisation (designer, design team, design department) performs the design activities. The design process of a specific project is further instantiated by allocating one or several design tasks to the resources involved (people and tools). The differences in design organisations are also a source of variation in design.
- Finally, it is the designer who carries out the design task through cognitive activities, through communication and collaboration and through interaction with tools and objects. The theory clearly shows via the model of cognitive processes in design that the design relies on his personal knowledge and experience. Design is also a learning process, not only by search, by interaction with people,

objects and tools but also by accumulation of the knowledge developed during design (the consolidation process). Design is definitely knowledge-intensive.

What was not addressed in the current version of the theory is an extended description (a) of the processes, the structure, the culture and the behaviour all kinds of design organisations and, (b) of the designer's activities other than the cognitive activities and the retro-action of these activities on the cognitive processes.
Along the same lines, no profiles of designers have been analysed or described: 'a designer is somebody who designs' whatever his position in an organisation and in society, and as stated before, the level of (relevant) knowledge and experience is up to a certain point, relative to the design task at hand.
As more progress in cognitive science is still needed in this challenging area, the aspect of emotion (affects) that, in our mind, is quite important for describing intent, relations between people and artefacts, interactions between designers and stakeholders and the motivation and the persistence of a designer, was only marginally dealt with.

The theory is articulated on a double perspective on design: the neutral, external perspective as found in the concepts of projects, design space and (abstract) design process and the agent-centred perspective where the interactions between agents and artefacts and the cognitive activities of the designer, is concerned. It may help (junior) designers in a better understanding of their design situation and for better dealing with the issues they are facing.

To summarise, the theory illustrates that design goes beyond a technical activity (related to the artefact), proper to a given domain of knowledge and experience. It is also a cognitive (the cognitive activities of the designer) and social activity (the involvement of stakeholders and the interactions within a design organisation).

5.2 Conclusions

5.2.1 Fulfilling the requirements

Whether the requirements put forward at the start of this undertaking are fulfilled is a matter of appreciation and interpretation of both the requirements and the results. When examining the three requirements, one can state that, as to

<u>Comprehensiveness</u>

The theory is quite comprehensive. It is not focused on one specific aspect of design but it establishes relations over a wide range of themes: the project, the artefact, the design space, the design process, the design organisation and the designer himself. It addresses the topics considered of major importance by Dorst (2007).

The general character of the theory

The theory is general in the sense that it has not been aimed towards particular design domains, particular artefact-types, particular design organisations, particular design situations like professional design, nor at particular profiles of designers. This level of generality has been (hopefully) achieved by using abstract and common terms and by avoiding terms that are proper to a limited set of domains. Moreover, the theory does not assume that design is a completely explicit nor rational process.

Explanation capability

The theory proposes a whole rationale starting with the project intent and uncertainty, over design as a knowledge construction activity in the design space, instantiated through the design organisation, up to the designer's activities and more specifically, the designer's cognitive activities.

More specifically, the theory proposes an explanation for: the project as the context for design, the role of design in a project, a criterion for terminating design, different types of design (preliminary, conceptual, functional, technical, …), the variable level of explicitness in design, the knowledge content to be developed during design, the design organisation as the context for the designer, the relation of the design process and the cognitive activities of the designer, the apparent 'chaotic' character of observed design activities that is associated with the designer's cognitive behaviour and the position of methods and frameworks that the designer may apply.

Alignment with other theories

- *The notion of design space*: most theories analysed in the Status Quaestionis use some kind of design space including this one, use the same paradigm but with different area definitions and variants. For example, (Grabowski, 1998) proposes a layered model of design space and (Tomiyama, 1987) uses the notion of function space, attribute space and meta-model space. In our view, the definition of areas or layers is a proposal to organise the design space but in fact, all these variants are variants of the same notion: the design space is a knowledge space. However, by not identifying the design space as a knowledge space, the theories seem to miss the opportunity to take into account, for a given design, of the starting position (i.e. what is already known) and the influence of the initial knowledge on carrying out the design process.
- *The design process and problem solving oriented theories*: the proposed theory appears to be in line with earlier problem solving oriented theories. They can be explained as theories that construct knowledge in the design space. In the design space, different areas as compared to the nominal content may be identified because of the fact that these theories focus at lot on the problem analysis part, while in the proposed theory, the focus is more on identifying the criteria for verifying and validating the artefact that is designed.
- *The relation with the C-K theory*: The comparison with the C-K theory of (Hatchuel and Weill, 2002, 2008) is somewhat more complicated. The present theory has a wider scope, where design is

concerned. The C-K theory seems to be able to address processes other than design alone, for instance, planning. The C-K theory does not specify why it is a specific theory of design. If concepts, as used in the C-K theory, are the result from explicit reasoning and are restricted to elements that can be formulated by using some language or symbol system, then the explanation offered by the present theory is wider for the reason it relates to all types of knowledge, even knowledge that is not language-bound.

Design as the development of cognitive artefacts: the content of the design space is compatible with the notion of cognitive artefacts in designing as developed by (Visser, 2006). The proposed theory is however much more specific as to the nature of the cognitive artefacts to be developed (see the nominal content of the design space).

5.2.2 Use and usability

When it comes to the use and usability of the theory, the theory is certainly not a method or a methodology. Nor is it able to replace theories that are proper to a specific domain of design. Nevertheless the theory may be useful in specific areas where:

<u>In practice</u>

- For designers, in understanding multiple functions artefacts may fulfil for people and in understanding that cognition of stakeholders is organised differently as compared to their own and for helping them in reconciling the different viewpoints. Indeed, the artefact as expected and as used is not (necessarily) the artefact as designed.
- For designers, in developing meta-cognition about design i.e. organising their personal knowledge and becoming aware that they design with their whole personality and all their knowledge and experience. In our view, a theory as this one has to be appropriated i.e. acquired, absorbed and integrated with the knowledge of the specific person (he may even develop a personal version of it).
- In communication and collaboration on multi-disciplinary projects where project members try to develop and common understanding and make sense of their design respective activities and where they may need a reference framework about design.

<u>In education and training</u>

- In design education and training for explaining to students and experienced designers, in order to explain what design is about.

<u>In research and development</u>

- For design research as a source of hypotheses that may be (in)validated and that may lead to a refinement of the theory.

- For the development of tools that would be able (a) to present knowledge according to the areas and sub-areas that have been defined in the design space, for a specific project and (b) to track the actual behaviour of designers and derived from it, in an automated, intelligent way, best practices.

5.3 Perspectives

The theory presented in this thesis is a general theory of design; it is not a Universal Theory of Design as defined by Grabowski (1998). Nevertheless, the subject of design even considered at a general level is so complex that the theory has to be considered as a theory version 1.0. Ideally, the development should be continued by group(s) of people (a network) from different backgrounds.

Here are some perspectives for further work:

- *Complementing the theory*: obvious extensions to the theory are in the contribution on the design organisation and on the designer's activities. At this stage, only the cognitive activities have been described. The other designer's activities should be developed in a cognitive perspective and integrated with the contribution on design organisation so as to start to establish the link between individual and group behaviour.
- *Formalising the theory*: work can be undertaken so as to formalise the theory. In analogy, with the axiomatic design theory of (Suh, 1990) the general theory of design of (Tomiyama &Yoshikawa, 1997) and the C-K theory of (Hatchuel and Weill, 2002, 2008), formalising the theory may provide a theory that is more compact and with a deepened theoretical foundation.
- *Extending the theory*: the theoretical framework allows situating domains of knowledge able to enrich the theory:

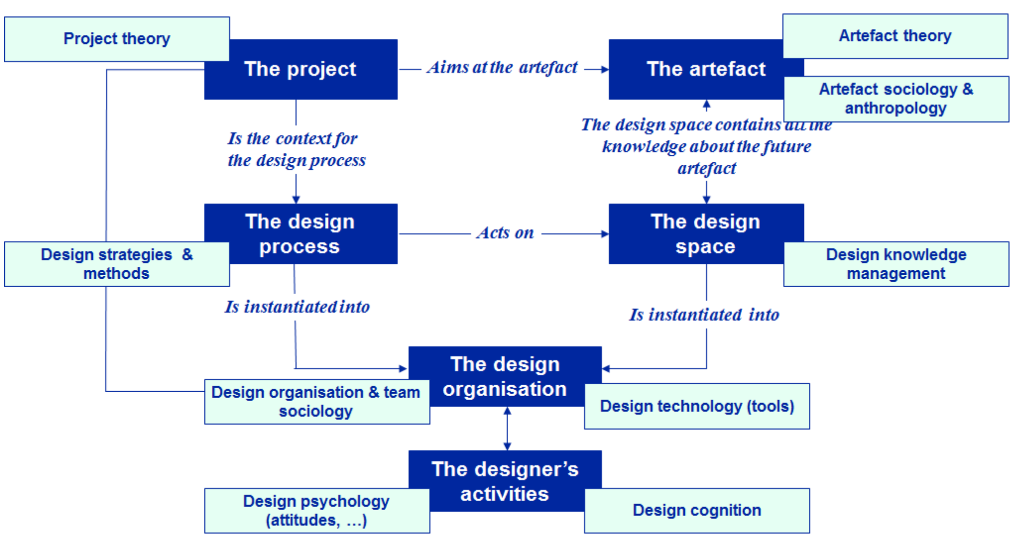

Figure 32: Orientations for further research and development

6 KEY CONCEPTS AND DEFINITIONS

Concept	Definition
Agent	The person who is involved in action or interaction.
Artefact	An object that comes into being through human intervention.
Artefact embodiment	The concrete (real) aspect of an artefact.
Artefact ergonomics	The way how an object is perceived through the five senses by a given agent in a given situation.
Artefact function	The (potential) value or utility an artefact has for a given agent in a given situation.
Artefact function : identity-related	The aspects of an artefact function that represent value or utility for the agent where world vision, self-image, internal states (affects) are concerned.
Artefact function : social	The aspects of an artefact function that represent value or utility for the agent where his interactions with others are concerned.
Artefact function : technical	The aspects of an artefact function that represent value or utility for the agent where his interactions with the physical reality are concerned.
Artefact life-cycle	The anticipated or actual series of states that an artefact will undergo or is undergoing after design until destruction.
Artefact type	An attribute allocated to an artefact by an agent so as to relate the artefact to other artefacts, for cognitive purposes and/or for communication purposes.
Cognitive activities	Mental activities, using content of the long-term memory, that activate, transform and evaluate content in the short-term memory of an agent.
Cognitive content (knowledge)	Static content of the long-term memory that can be activated by the cognitive activities.
Cognitive routines (know-how)	Content that can be mobilised and act as cognitive activities.
Design theory framework	A conceptual framework that establishes main relations between key design concepts.
Design (definition)	(1) The intent for ultimately creating a new artefact, (2) The process of imagining and specifying this artefact, (3) The result of the above process.
Design criteria	The criteria used in design so as to verify the adequacy of the artefact that is being specified by the design process.
Design (nature)	Given a project with the intent to create or to modify an artefact, design consists of cognitive activities and interaction activities with objects and people, so as to build up a satisfactory level of knowledge

Concept	Definition
	about the artefact.
Design (purpose)	The purpose of design is to reduce the uncertainty inherent to the project (where the artefact is concerned) to an acceptable level.
Design requirement	Statement about the properties of a future artefact, deemed necessary or a least desire-able.
Design knowledge	The knowledge about the future artefact that is being created during the design process.
Design phase	The project phase that is primarily devoted to the design of the artefacts. There may be different design phases in a project.
Design organisation	The set of human and other means that are involved in the design process resp. design phase.
Design space	A virtual space where the design knowledge is constructed.
Design task	The part of the design phase that is allocated to a designer.
Designer	The agent who designs i.e. who carries out a design task.
Designer's interactions	Interactions a designer has with people (communication and collaboration) and with existing objects (perception and manipulation). Together with the cognitive activities, the interaction activities carry out the design process.
Project intent	The explicit objectives and implicit drivers that push people to act and to aim at changing an existing situation in a future situation.
Project	The set of activities aiming at transforming an existing situation into a future situation.
Situation	That part of reality considered relevant by one or several agents.
Situation AS IS	The starting point for a project.
Situation TO BE	The situation that is targeted at by a project.
Stakeholder	1 person who is involved in or affected by a project or its results.

7 APPENDICES

List of appendices

1. Appendix to: The project as the context for design
2. Appendix to: The artefact as the object of design
3. Appendix to: The designer’s activities

7.1 Appendix to: The project as the context for design

In the human and natural environment change is always going on. Humans themselves continuously change. Change can have natural causes but change can also be caused by human intervention. These human-directed changes are called projects.

Projects are driven by intent. They are supposed to last a limited time[24] and at the end to have performed a transformation or change as compared to the starting situation. Projects or at least the intent is pre-existing as compared to design: the intent to change and to act are pre-conditions for considering design.

7.1.1 Project concepts

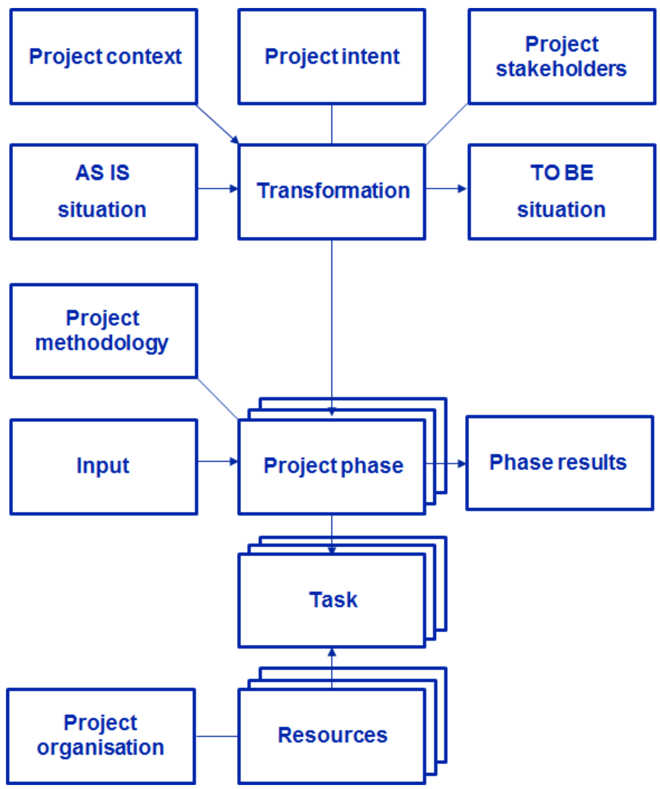

Figure 33: Project concepts

In order to be able to better distinguish the elements that pertain to the project and those that relate more strictly to design and in order to be able to situate the role of design in a project, the basic elements of a project are recalled. This is supposed to be common knowledge that can be found in many project

[24] By their very nature projects, as opposed to continuous action, are supposed to last a limited time. However, the scope of subjects and issues that are taken into account can go beyond the time-span of the project. A product development project that in itself lasts a limited time may address the whole life-cycle of a product from the early definition of the product till its final disposal.

management methodologies (e.g. Prince2) or bodies of knowledge (e.g. PMBOK). Some remarks have been made in order to have projects being understood as a most general process.

- *Agent* or *Actor*: the person who acts

- *Intent, objectives and constraints*: the intent results from a series of explicit and non-explicit drivers which move people to act. The intent, for a group, results from the individual intents of the group members. Intent implies a certain level of consciousness. This does not imply that all activities of the transformation are necessarily performed in a conscious way. *Objectives* are the socialised expression of the drivers. This expression of drivers may be incomplete. Hence, in determining the intent, objectives as well as hidden drivers have to be taken into account. Objectives and drivers are restricted by accepted *constraints*.

  The intention is thus a combination of objectives, drivers and of constraints.

  In larger projects, the intention derives from a group of people who act on and with the sponsor in all kind of manners: they are the stakeholders (see below). In such situations, the transformation intention results from the intentions of the sponsor and the other stakeholders, intentions which do not necessarily converge. Sometimes a whole exercise of consensus building is required before the objectives of the project can be formalised.

  In fact, a project is about change and transformation. The transformation occurs in a technical, economic, social (organisational) and political context and the introduction of one or more artefacts retroacts on this context. The change may be limited to the organisation directly concerned (like moving to a newly constructed building or introducing a new information system) or lead to changing the market conditions (like the introduction of tablet computers). Junginger (2008) analyses this for product development.

- A *situation* is that part of reality that is considered relevant by the project. A situation is the set, dependent on time, of the entities (people, objects) and the relations between these entities. It has to be noticed that the notion of situation involves a considerable part of subjectivity or inter-subjectivity where groups of people are involved. In projects, two situations are often considered: the AS IS situation i.e. the starting point and the TO BE situation (the target situation the project aims at). The change between AS IS and TO BE constitutes the *transformation* the project is intended to perform. Projects also consider AS COULD situations which is another name for alternative.

- The set of entities that is focused on is called the *object* of the transformation resp. of the project. The entities that are not focused on, but nevertheless considered (less) relevant, form the *context* of the object of transformation. The object of the transformation resp. of the project is that what is intentionally being transformed. There may be collateral changes to other objects or pre-requisites on the context for the object to be transformed (such as training people before giving them a new job). The TO BE situation may consist of one artefact, several artefacts or a complex combination of interactions between new, modified and unchanged artefacts and people. An artefact may be a building, a machine, a movie or a symbolic object like a totem. In organisational transformation, the object of transformation is often an existing organisation; the TO BE situation is the organisation that shows a modified behaviour through changes in its structure, people, processes, tools, capabilities and culture.

- The project intent aims at immediate or at delayed *results*. The intent may be focused on the change of a given situation (the object of the intent) or at the impact of the changed situation (other transformations triggered by the changed situation (causality chain)), for instance, introducing new technology that leads to organisational change. There can be a time-delay between the moment the TO BE situation is achieved and the moment the expected impact of this TO BE situation is reached. For example, there can be a considerable time delay between the realisation of a new airplane and the moment the investment in design and production becomes profitable. Projects results are typically: the actual change as compared to the AS IS situation, the value of reaching the TO BE situation, whereby the 'net value = the value – waste' is compared to the transformation cost, the impact on the position of the stakeholders during and after the project, unexpected beneficial or negative changes and second-order consequences of the results. Associated results can derive also from performing the project, in achieving learning and capability development. In fact, the completion of the project may start a chain of events that are not all intended and that yield collateral benefits or costs.

- Project *stakeholders* are the people involved and/or affected by the project and its results. Stakeholders are not only those directly involved in the project (users and people in charge of operation, maintenance, repair and disposal) but also people affected by the results of the project like the people who will have to live close to a new railroad. One can find in (Littau, 2010) an analysis of the development of stakeholder theory in project management literature. The importance of stakeholder involvement is recognised and the type and depth of involvement is examined. However, stakeholders can also be recognised without explicit involvement, in the case of innovative projects or in the case of the 'lone inventor' who aims at serving an imagined user.

- Projects require *resources* in order to be realised. The resources can be people, tools (machines) and finance. In a narrow definition, the project organisation is the *structure* of the project linking the different people and resources involved. In a broader definition, the *project organisation* is the set of people and the device(s) that carry out the project. For individual projects, the project organisation is obviously reduced to one single person who holds the intent and who realises the project with or without tools. In other cases, the project organisation is more complex and involves an organisation structure where the roles of the people are specialised such as: sponsor, designer(s), people in charge of realisation, operators and users, people in charge of maintenance and people in charge of repair and upgrading. The project organisation can even evolve over time as other competencies and capabilities are required for the different phases of the project.

- At the start and during transformation there is *uncertainty*: nobody has complete information about the AS IS, about the TO BE situation and about the contingencies of the transformation processes. This uncertainty relates for the artefact, to the number and type of variables for which decisions have to be made. Depending on the viewpoint adopted, uncertainty means risks or opportunities associated with a changing situation.

- The uncertainty associated with transformation involves the possibility of divergence and failure. Unless unlimited and or inexpensive resources, including time, are available, there is a need to focus on the objectives and on the targeted results so as to ensure that the value associated with the results of the project is achieved, or at least, is in balance with the project costs. Most often, this leads the project to be decomposed in *phases*, reflecting the steps in commitment for the project to proceed. This phasing decomposes the project activities in manageable steps whereby each phase delivers a specific result. A typical (but certainly not unique) decomposition in phases is as follows:

Phase	Milestone and associated result
Study	Object of transformation & design defined
Visioning and strategy	Overall direction of possible and necessary action defined
Planning and design	Activities and artefact specified
Realisation	Activities performed and artefact developed and completed
Commissioning	Artefact implemented into its operating context
Operating	Artefact used, maintained and upgraded as needed
Decommissioning	Artefact deactivated
Disposal and destruction	Artefact disposed, archived or destroyed

Table 16 : Typical project decomposition in phases

The list of phases should be considered as examples of phases by nature: it does not mean (a) that the phases should be executed according to a pure sequence, and (b) that phases cannot be decomposed in sub-phases.

An alternative to a pure sequence of project phases (the 'waterfall' model) is the 'spiral' model as illustrated in (Unger, 2010):

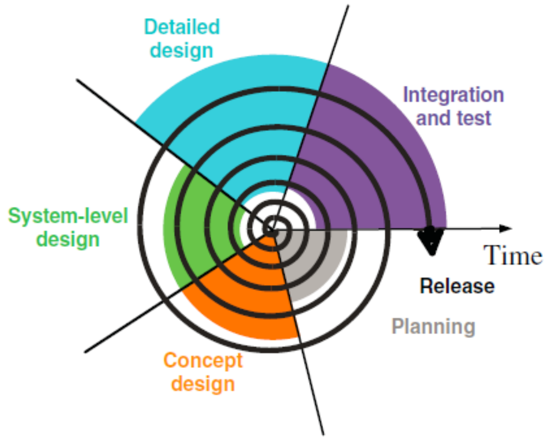

Figure 34: The spiral development model (Unger, 2003)

The figure illustrates (a) the iterative development of a product in successive releases and (b) different stages in design. It illustrates as well that the design process (for this project approach) is subdivided in different design 'phases' going from concept design, through system-level design and to detailed design.

- A project may be *incomplete* as compared to the above list of phases either by intent (projects aimed at training, simulation or exploration and at knowledge build-up) or de facto, when it proves to be unfeasible for technical, economic or social reasons. Other reasons are uncontrollability or the lack of stability in objectives or in scope. In this perspective, the project *feasibility* is the possibility to realise the project intent and the corresponding transformation within a given period of time, taking into account the limited available resources.

7.1.2 The variety of projects

Projects are quite various. A first distinction that could be made is by the number and type of agents (sponsors, stakeholders, resources) involved: mono-agent and multi-agent projects. Multi-agent projects most often require a higher level of explicitness in order to ensure proper communication and collaboration.

In order to illustrate the variety of projects, one can find below a table with examples of projects, sorted according to following criterion: the focus i.e. whether the project is oriented towards the agent himself, towards a group of people or towards technology i.e. tools to transform the physical environment. Obviously, there may be combinations. The table indicates also the nature of the transformation that the project achieves, the object resp. the artefact that is transformed, the result of the transformation, the conditions for termination of the project and finally, whether the project involves design and or planning.

The table is meant to be illustrative; it is not a typology of projects.

<u>Note</u>

In this context, social means dealing with several people, taking into account their interactions.

7.1.3 Examples of projects

Group	Transformation nature	Object of transformation	Transformation result	End of project	Design vs. planning as intermediate step?
Personal projects	Playing a game (sports, self-invented games, ….)	The game instance	Change of configuration of the game	By milestone (end of game) By application of certain rules or when the game has reached a certain configuration	No, unless some strategy and tactics previously developed are applied.
	Modelling/representing an object	The representation on a medium	The medium modified by lines, spots of colour, inscriptions, symbols	When the modeller is satisfied	No, unless some method is applied
	Self-learning	The agent himself	The agent's knowledge and his personal reference framework(s)	When the agent is satisfied	Planning of the topics to be learnt and of the process of learning, depending on the method applied
Social-oriented projects	Consulting	The client The consultant	Internal states (abstraction made of the spatial configurations) of the client and the consultant during the consulting process: both are building up knowledge and experience	Further to the application of certain pre-defined rules concerning time and/or money spent, or further to the internal state of the client (his need being satisfied)	Planning
	Change management	The client The consultant The people and organisation subject to change	Internal states (abstraction made of the spatial configurations) of the client, the people involved and the consultant during the change process	Further to the application of certain pre-defined rules concerning time and/or money spent or further to the internal state of the client (his need being satisfied) and/or of the people involved	Planning
	Political campaign	The perception of the politician The constituency The politician	The (non-) election of the politician The position of the politician at local, regional or national level The position of the politician in different contexts (family,	Further to the application of certain rules pertaining to the election process or by exhaustion of the campaign resources	Planning

Group	Transformation nature	Object of transformation	Transformation result	End of project	Design vs. planning as intermediate step?
			business)		
Technique and technology-oriented projects with a personal component for the agent involved	Use of a tool	The object the tool is acting on	Depends on the use of the tool and the object it is acting on. Change of the object the tool is acting on.	Further to the application of certain rules, or on the internal state of the agent or failure.	Planning Possibly, training of the agent
	Interacting with a (existing) computer	The computer configuration	The internal states of the computer (its programmes and data)		No planning and no design Possibly, training of the agent
Social-oriented projects with a strong personal component for all those involved	One-to-one communication	Both people involved in the communication process	Internal states of the individuals involved in communication	Depending on the internal states of the individuals involved or whenever one of the agents terminates the process	Planning
	Meeting	All people involved in the meeting process	Internal states of the individuals involved in the meeting	By application of certain rules or by exhaustion of the agents/resources	Planning
	Training	All people involved in the training process	Internal states of the individuals involved in the training	By application of certain rules or by exhaustion of the agents/resources	Planning Design of the training material
	Arts performance	All people involved in the performance	Internal states of the individuals involved in the performance. Internal states of the individuals watching the performance.	By application of certain rules or by exhaustion of the agents/resources	Planning of the performance Design of the arts artefact (composition, choreography, set, ….)
	Elections	Constituencies Leaders looking for being elected	Internal state of the electors Configuration of the political system (majority/minorities)	By milestone (election closure) By application of rules	Planning
Social and technical-oriented projects	Running a ship	The ship voyage The ships configuration The ships path (trajectory)	Internal and external states of the ship	By application of certain rules (reaching 'destination') By accident or destruction of the ship	Planning

Group	Transformation nature	Object of transformation	Transformation result	End of project	Design vs. planning as intermediate step?
Technique and technology oriented projects	Producing a car	The materials and components processed in the production and assembly process The car that emerges during the production process	Change in structure of the car (emergent structure) Change in configuration (integration of components and materials) Change of location and orientation (move: translation and or rotation)	By application of given rules to determine the status: 'car completed'.	Design of the car and ensuring manufacturability Design of the realisation process, if new Planning of the realisation process
	Maintaining a car	The car	Minor or major changes in internal and/or external configuration (components, consumables). Major changes are for example, pertaining to body work/repair	By application of given rules to determine the status: 'car is maintained'	Design of maintainability of the car (specific properties of the object)
	Operating a car	The car in context (the road)	Controlling the car through actions mediated via control handles and features that lead to changes to internal and external states of the car.	By application of given rules i.e. when the goals associated with the operation of the car have been achieved, or, by exhaustion resp. the destruction of the car or further to the absence/illness/death of the operator	Design of the operating environment Planning of the activities
	Controlling an object	The object	Internal and external states of the object. The To Be state looked for before and during the controlling process (the object configuration may the goal or the object is a means to achieve higher goals).	When the To Be configuration has been achieved and/or when the higher goal has been achieved.	Design of the control features Planning of the control processes

Group	Transformation nature	Object of transformation	Transformation result	End of project	Design vs. planning as intermediate step?
	Disposing of a car	The car	Components that may be re-used Materials possibly downgraded as compared to their original state and that have to go through an upgrading process so as to be re-used	When the car is decomposed in re-usable components and/or materials, either re-usable or considered as waste	Design of the disposability of the car Planning of the disposal process
Complex social-technical projects with a strong personal involvement for those in charge	Apollo programme	Multiple artefacts: capsule, moon-lander, launcher, guidance system, tracking system, etc..	Man on the moon and safe return to the Earth	Repeated landings on the moon terminated by a political decision (budget restrictions and vanishing interest)	Design of hardware and software and of the supporting organisation Planning of the programme and the different activities and allocation of resources
	The Manhattan project	The atomic bomb	The bomb as such (multiple instances) The military capability for terminating the World War II The strategic dominance of the USA	Delivering three bombs (the actual use was pertaining to other projects and initiatives)	Design of the bomb (two types) Planning of the activities
	Major architectural projects for self or group glorification	The buildings and their environments	The buildings The changed environments The prestige of the politician(s) The prestige of the group concerned	With the achievement of the intent or with the exhaustion of resources	Planning and design
	War	The battle front The war theatre	Occupation of the enemy territory Destruction or deep change in the enemy's political system Destruction of the enemy's forces	When the target transformation result is reached or by exhaustion of the resources of the parties involved	Planning (Possibly) the design of a new political system to be imposed on or to be appropriated by the enemy

Table 17 : Examples of projects

7.2 Appendix to: The artefact as the object of design

7.2.1 Agents, objects and cognition of objects

Preliminary notes

1. In the following statements, no distinction is made between natural and artificial objects as long as the statements apply to both categories.
2. In this section, we introduce some elements of cognition science that are explained in more detail in the section on the designer's (cognitive) activities. These elements are important for illustrating the subjective character of the interactions between agents and objects.

Agents and objects

As considered from the viewpoint of an agent, an object is a part of the subjective (his) reality, the agent is focusing on. The object must have a certain level of stability over time; this period of stability is related to the 'objective' properties of the object and as well as to the observational and memory capabilities of the person: the object must be observable either directly or indirectly. In other words, an object is some part of part of reality that (a) can be isolated from another (discreteness) and (b) that "exists" over a certain period of time, in the real world as well as in the mind of the agent. The relation to the mind of the agent implies that, for example, at a given moment, one can focus on the car at standstill, seeing the car as a whole, then focus on the engine or on one of the tyres, and still, later on the control of the car while driving. This illustrates the generic character of the notions of object and artefact and at the same time, the subjectivity (related to agent) and the relativity (related to the context and the type of interaction) of these notions.

Agents and cognition of objects

Cognition is the relevant information that an agent gathers and memorises over his life-time. Where objects are concerned, he does so during perception and interaction with objects and during communication and collaboration with others, about objects. More precisely, cognition involves cognitive content (knowledge) and cognitive capabilities (experience and skills), which both evolve at each interaction. The basic structure of cognition consists of episodes i.e. memorised sequences of interaction (including perception) with a set of people and or objects. The interactions between the agent, the people and the objects as well as the interactions between the other people and the objects, and the successive states of all these elements, as they are memorised, constitute the episode. Contextual elements deemed relevant are memorised too. This relevance is agent-dependent.

The content of the episodes is consolidated in the long-term memory of the agent and semantic structures are built-up in terms of cognitive hierarchies (for example, categories) and networks (relations between elements of totally different episodes (for example, remembering thinking of design while wandering and observing a remarkable bird). Networks develop through the identification of elements common to several episodes, for instance, the use of a type of screw in different objects. These structures are continuously updated. It is in such a way that the concept of object emerges and develops as a set of constant properties during successive interactions. It should be noticed that at each interaction, cognition is updated and most frequently, enriched. This implies that what an agent ‘knows’ about an object is dependent on: (a) the cognition he has already of the objects or that particular object, (b) the direct interaction with the objects and (c) the cognition he builds up during communication and cognition with others, about objects. Hence, a large part of this cognition is subjective and constructed.

When an object is minimally known (after a first interaction), the agent who interacts with the same or a similar object, builds up an episode with one or more configurations of the objects; these episodes enrich the pre-existing cognition. The cognition of the object is also progressively enriched with more and more known configurations of a known object. Conversely, the configurations may be defined as instances of the object in different contexts. Unless a specific instance of an object is referred to (‘that’ car, ‘my’ bicycle), objects as known by an agent are concepts (abstractions) that refer to possibly different typologies of objects or to a structure linking the different configurations. For example, for a given person, an organisation can be at the same time: a building with the name of the organisation, the working place for an individual, the group(s) of people he is usually working with, the working processes that have to be performed, the rules and standards that have to be applied and that are described in the organisation’s reference handbook. ’Organisation’ is the concept that integrates these different views.

The nature of artefacts

(Kroes, 2002) argues that: …”technical artefacts have a dual nature: on the one hand they are physical objects (man-made constructions) that may be used to perform a certain function, on the other hand they are intentional objects since it is the function of a technical artefact that distinguishes it from physical (natural) objects and this function has meaning only within a context of intentional human action.” This illustrates the subjective character of what is perceived as an artefact by an agent.

7.2.2 Types of objects and artefacts

A sample of design literature shows that design is involved with a huge variety of artefacts such as buildings, cars, cities, communities, digital artefacts, evolving artefacts, fabrics, human computer interfaces, information, landscapes, organisations, products, sounds, services, systems, technical artefacts, textiles, virtual artefacts, wearable artefacts and so on.

Some authors have tried to establish classifications described in (Magee, 2004). For complex systems some classifications have been proposed (apparently, these are not standard classifications):

- MIT The engineering system division (2002): system, complex system and engineering system
- (Von Bertalanffy, 1968): static structures, clock works, control mechanisms, open systems, lower organisms, animals, man, socio-cultural systems, symbolic systems.
- (Miller, 1986): cells, organs, organisms, group, organisation, society, supra-national system
- (Paynter, (1960): services, structures, instruments, vehicles

There are many more possible classifications and types of classifications (by degree of complexity, by branch of economy or sorted according to different attributes). In the context of design, with the assumption that artefacts have to have relevance i.e. to fulfil a certain function for users or consumers, categories based on human needs might be useful. However, the question remains whether an exhaustive classifications of human needs is actually possible, as new needs emerge when previous needs have been satisfied.

Classifications may be interesting for defining and describing objects, communicating about them or for using the classification criteria in qualitative assessments. A typology may also be useful so as to stimulate and orient imagination, for instance, when required properties are being defined by referring to what is known about existing objects.

Types of and interaction with artefacts

Having in mind the fact that artefacts are being designed with some users (possibly imagined) in mind, a classification that is focused on interactions between agents and artefacts may offer some benefits because the functionality of an object is strongly related to the type of interaction the target users will have.
In the proposed classification, the first distinction is between natural and artificial objects. For the latter, a distinction is made between technical and symbolic artefacts, where technical artefacts are characterised by their physical utility (acting on the physical environment in the case of tools) and creating environments for protection or territory definition. Hence, the distinction between technical and symbolic is associated with the role of the artefact.
A further decomposition of artefacts is between 'real' (technical or symbolic) and virtual objects. Technical and symbolic artefacts are embodied on or in a medium that has a certain material stability over time: unless they are actively transformed due to human action, their stability is influenced by nature (degradation or natural destruction). Virtual objects require an active resource so as to embody them: a web page, a GUI (Graphical User Interface) window or to execute them (a computer program or a movie or an opera) or even an actor in the case of a theatre play.

Classification			Interaction type
Level 1	**Level 2**	**Level 3**	
Natural objects	(Material)		• Perception • Moving: translation & rotation • Manipulation (using as a tool) • Transformation: modification of form • Transformation: modification of the (internal) structure
Artefacts	Technical artefacts	Devices/tools	• Perception • Moving: translation & rotation • Manipulation (using as a tool) • Transformation: modification of form • Transformation: modification of the (internal) structure
		Environments	• Appropriation (territory) • Occupation
		Autonomous objects	• Controlling (the more autonomous the

Classification			Interaction type
Level 1	Level 2	Level 3	
			object, the less control can be exerted)
	Symbolic artefacts		• All the interactions that can be applied to devices and/or to environment, where the embodiment of the object is concerned • Appropriation of symbols so that they can referred to and that possibly help in re-structuring cognition
	Virtual objects	Declarative	• Appropriation of information (as new cognition)
		Procedural	• Appropriation of rules/procedures so as to apply them through routines • Appropriation and execution of methods (as new cognitive capabilities)
	Integrated combinations of several artefacts	Systems	• The interactions applicable to the different system components

Table 18: Types of and interactions with artefacts

Note

The above categories may overlap: a robot is a (relatively) autonomous artefact but is also a technical artefact. A cathedral meant to encompass the whole community is a technical artefact as well as a symbolic artefact. It is doubtful whether a single hierarchical classification might be defined. Classifications should be multi-hierarchical for the different uses and perspectives that may be adopted.

7.2.3 Examples of artefacts by function

The examples given below are to illustrate the typical function (the function as experienced by the agent) of some artefacts. They are grouped by classes according their relative weight in each of the function dimensions. It should be noticed that even these specialised artefacts may have a function in other dimensions too.

Class	Overall function	Example of artefact	Specific function
Identity-related	Sustaining life	Food	Energy for subsistence and growth
	Protection	Cloth	Protection, appearance
		Prosthesis	Recovering a lost capability or restoring the physical integrity
	Appearance	Jewel	Decoration
	Cognitive support	Paper for taking notes	Memory support
		Computer	Memory support & information retrieval
	"Nesting" and the organisation of space	Cave after modification	Protection, heating, territory definition
		House	Protection, heating, territory definition
		Interior arrangement	Territory definition

Class	Overall function	Example of artefact	Specific function
		Tent	Protection, heating, territory definition
Social artefacts	Standardised social interactions/ transactions	Services (person-to-person)	As a form of collaboration in society (providing help, compensating or complementing activities)
	Social tools	Communication tools	Telephone (voice) Computer network (data, multi-media)
		Coordination tools	(Expression of an agreed) procedure
		Knowledge sharing tools (data-bases, the Internet)	Tracking historical events Making information widely available
		On-line socialising tools (social networks)	Eliminating physical boundaries in socialising
	Social structure	Association	Allowing people to achieve common goals and to defend shared values
		Profit organisation	Organising resources for achieving profit in a given economical context
		Political institution	Organising society (a country, a region)
Technical artefacts	Help for direct action on the physical environment	Screwdriver	Extending personal physical capability for assembling
		Drilling machine	Extending personal physical capability for making holes or destroying objects
		Bull-dozer	Extending a group's physical capability
		Machines	Extending the capability to produce other artefacts
		Gun	Menacing, defending, killing
	Transport incl. exploration	Bridge	Crossing a natural obstacle
		Tunnel	Crossing a natural obstacle
		Car	Personalised road transportation
		Airplane	Personalised or mass air transportation, depending on the type of plane
		Space shuttle	Manned, re-usable space transportation

Class	Overall function	Example of artefact	Specific function
		Space probe	Exploring the solar system by robotic proxy

Table 19: Examples of artefacts by function

7.3 Appendix to: The designer's activities

Variants of cognitive tasks

Based on the generic model described under §3.8, cognitive tasks can be differentiated: (a) by their objective, more specifically by the target entities that are to be developed in the working memory (working space) and (b) by the cognitive content that will be activated by the agent on the basis on his knowledge and experience in general, and with respect to the specific cognitive task. Hence, it is possible to distinguish: decision making, problem solving, planning and design, or by the target content of the working space. This target content is a nominal one as the agent involved may delete or add entities depending on his understanding of the task and the focus he wants to put on specific themes.

It should be noticed that this list is illustrative so as to show the possible diversity of cognitive tasks. The present research has focused on design as a specific cognitive task; the other types have not been investigated in detail.

Cognitive task type	Working space	Typical target cognitive entities
Decision making	Decision space	• Options (alternatives) • Consequences • Evaluation criteria
Problem solving	Problem solving space[25]	• Problem components • Symptoms • Problem impact • Solution alternatives • Evaluation criteria • Solution impact
Planning	Planning space	• Objectives • Constraints • Activities • Activities structure (sequential and parallel paths) • Milestones • Resources • Schedule: allocations of activities to resources
Design	Design space	• See section of the Designer's activities

Table 20: Variety of cognitive tasks

[25] The entities on the problems solving space have been derived from the steps of problem solving as defined by (Simon, 1972).

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Résumé

Cette thèse relève d'une recherche visant à développer une théorie générale de la conception. Une telle théorie se doit de faciliter la compréhension en profondeur du phénomène 'conception'. Les théories actuelles traitent le plus souvent d'un ensemble limité de types d'artéfacts ou ont été développées dans un domaine particulier de la conception. Par ailleurs, elles n'abordent pas les aspects les plus importants de la conception de manière intégrée.
La théorie proposée vise à expliquer la conception en largeur. La théorie comprend un cadre conceptuel et une série de contributions qui traitent du projet en tant que contexte de conception, de l'espace de conception c.à.d. le lieu où les connaissances de conception sont développées, du processus de conception en lui-même, de l'organisation de conception et finalement, des processus cognitifs qui permettent de comprendre le comportement du concepteur en action.
Ces contributions constituent une première version de la théorie, large, car couvrant les thèmes majeurs de la conception et générale, car non limitée à certains types d'artéfacts ou à certains domaines de conception.

Mots clés : conception, théorie, projet, artéfact, fonction, espace de conception, processus de conception, organisation de conception, processus cognitifs

Abstract

This thesis pertains to research aiming at a general theory of design. Such a theory should enable the in depth understanding of the phenomenon 'design'. Current theories are most often dealing with limited types of artefacts or are developed in a particular domain of design. Moreover, they do not address the most relevant aspects of design in an integrated way.
The proposed theory aims at explaining design 'in the large'. The theory encompasses a framework and a series of contributions that deal with the project as the context of design, with the design space where design knowledge is developed, with the design process in itself, with the design organisation and finally, with the cognitive processes that allow understanding the behaviour of the designer-in-action.
These contributions form a first version of a theory of design that is comprehensive, covering the main topics of design and their relations, and general, i.e. not specific for particular types of artefacts or related to a limited set of domains of design.

Key word: design, theory, project, artefact, function, design space, design process, design organisation, cognitive processes