# On Synthesis in the Later Phases of the Mechanical Engineering Design Process

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# Abstract

Only 15% to 30% of product development projects require the development of new product concepts. This means that the majority of design projects are carried out within the embodiment design and detail design phases. However, the majority of the research studies on the mechanical engineering design process, or design process for short, have been focusing on the conceptual design phase. The embodiment design and detail design phases are considered to be more routine-like and less complex, but the existing embodiment design and detail design methodologies (a methodology consists in a design process model, with related methods and supporting tools) suffer from at least two shortcomings: they are not as thoroughly developed as conceptual design methodologies, and there is a lack of dedicated methods and supporting tools for the generative design activities (hereafter called synthesis) of these phases.

This thesis constitutes the first part of an overall research project whose goal is to contribute to the development of a support methodology for the synthesis activities in the later phases of the design process. As a first step, it has been decided to put the engineering designer, or designer for short, at the center of the study. As the designer is the primary user of a design methodology, it is necessary to understand the designer's thinking patterns, to clarify his/her skills and know-how, and to identify some common or specific actions to form the theoretical foundation upon which the support methodology can be developed. Thus the first step of this overall research project is to observe and analyze how the designer performs the synthesis activities in the later phases of the mechanical engineering design process.

There is a lack of empirical pre-knowledge of the embodiment design and detail design phases; this first step is therefore explorative in nature and aims at covering this research domain extensively. The design activity of six designers (three students and three experts) has been observed in depth under an experimental setup. Each of the participants had to solve the same problem: to design a support device for a hydraulic piston. The verbal protocol analysis method has been applied to extract a model of their design activities, both on a strategic and tactical level as well as in a problem-solving perspective. The findings concerning the problem-solving process show that the designer, though following a fairly structured approach, developed no more than two alternatives, rapidly selected one of them and then lengthily studied and developed this alternative. There was no systematic evaluation moment. The activity of solution finding, characterized by synthesis, is balanced by an activity of mechanical modeling of the problem, which serves to both understand the generated solution and to monitor its correctness. At the strategic and tactical levels, the experts' design process has the following pattern: rapid understanding of the problem;

consideration, very early in the process, of the shape of the parts and their interactions; concrete selection of materials; optimized selection of standard components; dimensioning of the joints. The early selection of standard components led to an early focus on the spatial restrictions and interface compatibility problems. On the other hand, the students reasoned about abstract mechanical structures, without defining the components until late in the process, and thus faced complications later on. A list of “weaknesses” observed on the part of the designers’ process has also been established.

The results of this explorative study now need to be further investigated; some complementary studies have to be carried out to statistically verify them. In addition to that, an investigation of the design activity in an industrial environment is needed in order to establish whether or not there are additional factors influencing the embodiment design and detail design phases.

**Keywords:** embodiment design, detail design, form design, descriptive mechanical engineering design model, problem solving, synthesis, verbal protocol analysis.

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I would like also to thank Per-Erik Andersson, lecturer at Machine Design, who helped me design the experimental protocol and analyze the experiments.

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Finally, I would like to thank my beloved Alexandra who, even though she knew that the licentiate thesis was just a preliminary to what would happen next, still accepted my hand in marriage.

Lund, February 2006

Damien Motte

# Publications

This thesis includes the following appended publications:

**Paper A**
Motte, D. & Bjärnemo, R., 2004, "The Cognitive Aspects of the Engineering Design Activity – A Literature Survey", *Tools and Methods of Competitive Engineering TMCE'04*, Lausanne.

**Paper B**
Motte, D., Andersson, P.-E., Bjärnemo, R., 2004a, "A Descriptive Model of the Design engineer's Problem Solving Activity During the Later Phases of the Design Process", *1st CDEN Design Conference*, Montreal.

**Paper C**
Motte, D., Andersson, P.-E., Bjärnemo, R., 2004d, "A Study of the Mechanical Design Engineer's Strategies and Tactics During the Later Phases of the Engineering Design Process", *16th International Conference on Design Theory and Methodology - DTM'04*, Salt Lake City.

**Paper D**
Motte, D., Andersson, P.-E., Bjärnemo, R., 2004c, "Comparative Study of the Student's Design Process: Implications for the Teaching of the Later Phases of the Mechanical Engineering Design Process", *1st CDEN Design Conference*, Montreal.

# Also published by the author but not included in this thesis

Motte, D., Andersson, P.-E., Bjärnemo, R., 2004b, "A Study of the Design engineer's Cognitive Processes During the Later Phases of the Engineering Design Process", *8th International Design Conference DESIGN 2004*, DS 32, Vol. 1, Dubrovnik, pp. 421-428.

Motte, D., Andersson, P.-E., Bjärnemo, R., 2005, "Elements for Improving the Teaching of the Later Phases of the Mechanical Engineering Design Process", *15th International Conference on Engineering Design - ICED'05*, DS 35, Melbourne.

Wang, P., Bjärnemo, R., Motte, D., 2003, "Development of a Web-Based Customer-Oriented Interactive Virtual Environment for Mobile Phone Design", *23rd Computer and Information in Engineering Conference CIE'03*, Chicago.

Wang, P., Bjärnemo, R., Motte, D., 2005, "A Web-Based Interactive Virtual Environment for Mobile Phone Customization", *Journal of Computing and Information Science in Engineering*, Vol. 5, No. 1, pp. 67-70.

# Table of Contents

**Appended Papers**

# 1 Introduction

*In the early days of research on engineering design, synthesis in embodiment design and detail design constituted a major area of study. Today this is not the case. The first part of this chapter will show that this research theme is still valid and necessary. The research problem, hypotheses and delimitations are then presented. Finally, the thesis is outlined.*

## 1.1 Background

For a long time, research on the mechanical engineering design[1] process has focused on the elaboration of an optimal process model. The belief was strong that significant parts of the design process could be, in analogy with the evolution of production systems, significantly supported by means of computerized tools to be more or less "fully automated". Research then pursued the task of finding the best methods that would ensure good product quality. For the last 20 years, however, a shift of focus has been taking place in research on the design process. The questions of the practical application of such methods as well as their learning began to emerge (Schregenberger 1985). At the same time, it was re-discovered that the engineering designer, or designer for short, the principal user of these methods, already possesses knowledge and competences that had been underestimated, such as earlier experience, diverse levels of creativity, or the capacity of coping with complex situations. Finally, it was noticed that the designer, though educated in these methods, seldom applied them in his/her daily practice (Pahl 1983).

The designer thus has increasingly become the center of focus as a key element in the improvement of the design process. From early works within the field of architecture (e.g. Darke 1979) and continuing up to the present, descriptive studies of the design activity have been developed, aiming at a better understanding of the design process as it is performed, rather than basing design process models on product characteristics as was done previously. These kinds of studies, previously disparate, now constitute an important area of research in the design field, with dedicated conferences (among others, the Design Computing and Cognition Conferences series and the Human Behavior in Design Workshops series). The studies in this area are mainly based on observations of the design practice, though frameworks for simulation are beginning to appear, opening new paths of investigation (see e.g. Sosa & Gero 2004). The research methods employed are either experimental (the designer or

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[1] The expression "mechanical engineering design process" will be hereafter shortened to "design process", whenever this denomination is unambiguous.

the design team are observed under controlled conditions) or "in the field", mainly in an industrial environment, where all the factors that affect the design process are present. The earlier works focused on the designer alone, but subsequently, design teams, interdisciplinary or not, are being equally (if not more) studied.

Although there is a large consensus in the research community about the different activities involved in the mechanical engineering design process, these are regrouped in different phases, depending on the "design school" to which one belongs. In this document, for the sake of simplicity, the different phases of the design process are regrouped as follows:

1. the activities of establishing and understanding the design problem, finding principle solutions and choosing the "best one" are labeled the *conceptual design phase*;
2. the activities of establishing the product architecture of the technical system, selecting components, and creating and fully dimensioning each and every one of the details are labeled the *embodiment design and detail design phases* (see Section 3.2.1).

Both are equally important. As Pugh (1990) puts it, "It is also a fact of life that poor or indifferent detail design can ruin a good, even brilliant concept; conversely, brilliant detail design will never rescue a poor or ill-conceived conceptual design." (Pugh 1990, p. 102). Moreover, most design projects are carried out within the embodiment design and detail design phases. Ehrlenspiel (1995) gives the following figures regarding the ratio of different design projects (Ehrlenspiel 1995, pp. 215-216) based on two different sources: According to the German Engineering Federation (Verband Deutscher Machinen- und Anlagebau - VDMA 1986), 30% of the product development projects concerned the design of product variants (only detail design), and 37% were adaptations of existing products (embodiment design and detail design). According to Romanow (1995), 70% of the product development projects are variant designs, 15% are adaptive designs. This means that only 15% to 30% of the product development projects involve the design of new product concepts.

However, very few empirical works on the embodiment design and detail design phases have been found in the literature. The reasons are manifold. The conceptual design phase aims at finding new product concepts, while the activities of the embodiment design and detail design phases *can* be routine design; thus creativity and novelty are enhanced during the first phase. The design problem is very ill defined at the conceptual level and the conceptual design activity is most often of an interdisciplinary nature, which further increases the complexity of the task. Finally, following Pugh's remark, the conceptual design phase is the first phase of the design process, and thus any failure at this level will compromise the following design activities. Although these reasons may explain the appealing nature of the conceptual design phase, the embodiment design and detail design phases are not to be neglected.

Embodiment design and detail design are complex activities. During the embodiment design and detail design phases, the designer "must determine the overall layout design (general arrangement and spatial compatibility), the preliminary form designs (component shapes and materials) and the production processes, and provide solutions for any auxiliary functions" (Pahl & Beitz 1996, p. 198). These activities are very dependent on each other (changing the component shape can induce change in the overall layout design), which adds to the complexity of the task. Moreover, the design has to be optimized. The quotation above shows as well that some auxiliary functions have to be developed during the embodiment design and detail design phases, the conceptual design phase dealing mainly with the development of the principle solutions of the main functions. This implies that creativity is still very important at this stage. The designer also works under the constraints of time and cost, since the tasks are better defined. At this stage the designer has to retrieve, combine and apply the requisite engineering techniques in a proper manner, which is heavily dependent on the task undertaken. According to Pahl & Beitz (1996, pp. 198-199) the embodiment design and detail design processes are "complex in that:

- many actions have to be performed simultaneously;
- some steps have to be repeated at a higher level of information; and
- additions and alterations in one area have repercussions on the existing design in other areas."

For a long time, the general attitude towards the support of the embodiment design and detail design activities has been to develop methods and techniques for the different sub-problems in the form of rules and principles, while letting designers define themselves their working process and the way to apply these rules and principles. In the literature, general plans for the main activities of the embodiment design and detail design phases have been developed, but a refined process at the detailed activity level is believed to be unnecessary: "In the embodiment phase, unlike the conceptual phase, it is not necessary to lay down special methods for every individual step." (Pahl & Beitz 1996, p. 203), or very difficult: "Form is hopelessly interdependent on the material selected and the production processes used. Further, the nature of the interdependency changes with factors such as the number of items to be produced, the availability of equipment, and knowledge about materials and their forming processes [make it] virtually impossible to give a step-by-step process for product design [embodiment design and detail design]." (Ullman 1997, pp. 185-186)

The overall purpose of the research project of which this thesis represents the first part has been to challenge this traditional view. The hypothesis behind this thesis is that it should be possible to contribute to the development of a complete design methodology that guides and supports the designer throughout the design activity of the embodiment design and detail design phases.

## 1.2 Research problem

Jones (1962) is the first work known to the author in the design field that used the terms *analysis* and *synthesis* to describe the design process. Used initially at a strategic level (as phases of the whole design process), these terms have been re-employed for describing two types of specific design activities. For Hubka (1988, p. 249), *synthesis* is finding a structure that satisfies the required behavior and specifications of a Technical System (TS); *analysis* is the finding of the behavior of the TS given its structure. SYNTHESIS is in this thesis defined for embodiment design and detail design as the combining of "the retrieval and the comparison of the relevant knowledge (mechanical, technical…) with the current design problem, [and] the putting together of the elements to fulfill the requirements from the design problem at hand. Synthesis is creative in the sense that it generates something new, not necessarily original, but that did not exist before" (Motte et al. 2004; from Pahl & Beitz 1996). Synthesis is here opposed to analysis, which comprehends the design activities of modeling and verifying the technical system developed. Both are also indissociable: the technical system to be developed is constantly checked out. In the interest of clarity though, and for lack of an adequate terminology, synthesis is here considered as a design activity wherein solution generation is predominant, while the analysis activities are the design activities in which the understanding and the verification of the behavior of the TS are predominant, and require methods and tools like multibody systems analysis, structural analysis, thermal analysis, electrical analysis, magnetic analysis and computational fluid dynamics.

The development of a model of integration of the analysis activities in the design process (including the conceptual design phase) is currently being undertaken by Eriksson & Burman (2005). Thus this part of the design activity is not considered in this work.

The overall goal of the research project is:

**To contribute to the development of a support methodology, including necessary tools, aiming at facilitating synthesis in the later phases of the mechanical engineering design process.**

Following the arguments developed in the background section, it appears necessary to start by gathering information from observed design processes rather than developing a model from scratch. Thus the first step of the *overall* research project[2], presented in this thesis, is to answer the question:

**How does the designer perform the activities of synthesis in the later phases of the mechanical engineering design process?**

The results expected from this first step should answer the following questions:

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[2] The research project that aims at contributing to the development of a support methodology will be called hereafter "*overall* research project", and the first step that constitutes this thesis "research project".

- Is there a design process pattern that the designer follows and, if yes, what is this design pattern?
- What are the flaws in the design activities performed by the designer?

The information gathered will be used as the foundation for the development of the support methodology. The observed design activity flaws will have to be taken into account in the development of this support.

## 1.3 Delimitations

The following delimitations have been applied to the research project.

- The domains of application of this research are both design education and industry. It is important for the student to learn and understand design methodology, but it is in industry that the methodology is meant to be applied.
- Only the activities of the design process within a product development process are considered in this thesis. The design activities and/or the design process within a technology development project are different, thus they have not been taken into account in this thesis.
- Embodiment design and detail design problems are manifold. Only static systems produced in small series, with few parts, are studied here.
- As in Pahl & Beitz (1996) and the VDI[3] Guideline 2223 (2004), no particular efforts are made to tackle in-depth issues in the establishment of the product architecture. Indeed, a whole field of research is dealing with these types of problems (see Ulrich & Eppinger 2003), like space optimization and modularization.
- According to Pahl et al. (1999a, p. 490), individual work represents more than 70% of the design processes. This must be even greater for the embodiment design and detail design processes, when less interdisciplinary work is *de facto* needed. Thus only individual designers are being studied.

## 1.4 Hypotheses

The following hypotheses have been applied to the research project:

- Synthesis can be separated from analysis, considering the definitions given above;
- The ability and experience required in problem solving differs between embodiment/detail design and conceptual design.

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[3] VDI: Verein Deutscher Ingenieure (Association of German Engineers).

## 1.5 Outline of the thesis

This thesis is constructed as follows:

Chapter 2 presents the research approach, strategy and the method of investigation.

Chapter 3 presents the frame of reference in which this work is embedded. First, the assumptions behind the actual design methodologies are presented. Then prescriptive design process models used as a basis for this study are described. Their limitations are then discussed and descriptive studies that related to this study are presented.

Chapter 4 presents the results of this study.

Chapter 5 discusses the research approach, the method of investigation and the results.

Chapter 6, finally, presents the activities needed to complete the *overall* research project as well as the goals for future research.

# 2 Research approach

*The research approach adopted here is pragmatic. This thesis is the first step in the* overall *research project described above, and is of an explorative nature. The implication of this approach is described in the first section. The second section explicates the research framework on which the empirical investigation is based. The third section describes the actual research process. The experimental method is explained in the last section.*

## 2.1 A pragmatic approach

As stated in the introduction, the *overall* research project intends to develop a support methodology for synthesis in the later phases of the design process and, in this regard, the observation of designers is simply a means to that end. Moreover, knowledge in the applied sciences has a short life cycle, and any descriptive model of the designer in action is provisional, as will be the methodology developed. It is thus necessary to map the field of study (synthesis in the later phases of the design process) in order to list the domains of priority. These domains of priority can depend on conjuncture (important because the applications of these results can have an important societal or political impact, for example) or on the contrary these domains can be invariant for some time, meaning that their study enjoy prolonged usefulness. It was thus decided that the study of synthesis would be primarily explorative in nature, thus covering the widest range of elements that can be helpful in the development of the methodology, in order to prioritize the ones that should be more deeply studied and validated later on.

Which elements should also be prioritized? In theory, the only result whose validity should be tested is the support methodology itself, whether based on the explorative study or not, by means of statistics or case studies. Ultimately, the origin of the support methodology is not important as long as the support methodology gives good results. However, if the development of a methodology is based on wrong or unfounded bases, then this methodology is certainly less likely to be successful. Moreover, a complete methodology is extremely difficult to validate, which is the reason why the validity of the current methodologies is still questioned. So only the elements that are fundamental to the development of the methodology should be validated. This is also true of the elements from which parts of the methodology can be directly deduced. This means also that any validation is contingent on the development of the methodology.

If the study is explorative in nature, the knowledge extracted is not statistically valid, and hence this knowledge cannot claim to be grounded. There are some ways around this issue, without falling into epistemological considerations. First of all, some pieces of information have an obvious character and do not need to be validated. It has been noticed, for example, that all the observed designers who tried to dimension the technical system to be designed made errors based on non-proportional sketches and had to re-dimension the system (see Section 4.2). Whether this information is valid (we can reject the hypothesis that the designers who draw non-proportional sketches make no mistakes) or not is not important: *some* designers made incorrect dimensioning because of non-proportional sketches, which means that this parameter should be adopted as a recommendation for the designer or integrated in a design-supporting tool. Other information elements are less obvious, or are not a direct deduction from the observation, but an inference or generalization of it (see for example the descriptive Problem-Solving Process [PSP] model Section 4.1). If these elements were later on to form the core of any support methodology, they should somehow be validated to ensure that at least the methodology is grounded. If the support methodology or part of it is directly deduced from these elements, this part will *de facto* be also valid. The minimal requirements for the presented results are that they should be falsifiable, have an inner coherence and thus lack redundancy (for example by being formally described).

This need of validation following the pragmatic approach is represented in Table 2.1.

Table 2.1 Need of validation of the different elements of the description of the design activity following the pragmatic approach

| | ***Part of the methodology directly deduced from the elements*** | ***Non-directly used in the methodology*** | |
|---|---|---|---|
| | | ***Core of the methodology*** | ***Auxiliary elements*** |
| ***Obvious elements*** | No need of validation. | No need of validation. | No need of validation. |
| ***Non-obvious elements*** | Need to be validated, to valid the corresponding part of the methodology. | Need validation to ground the methodology. | No need of validation. |

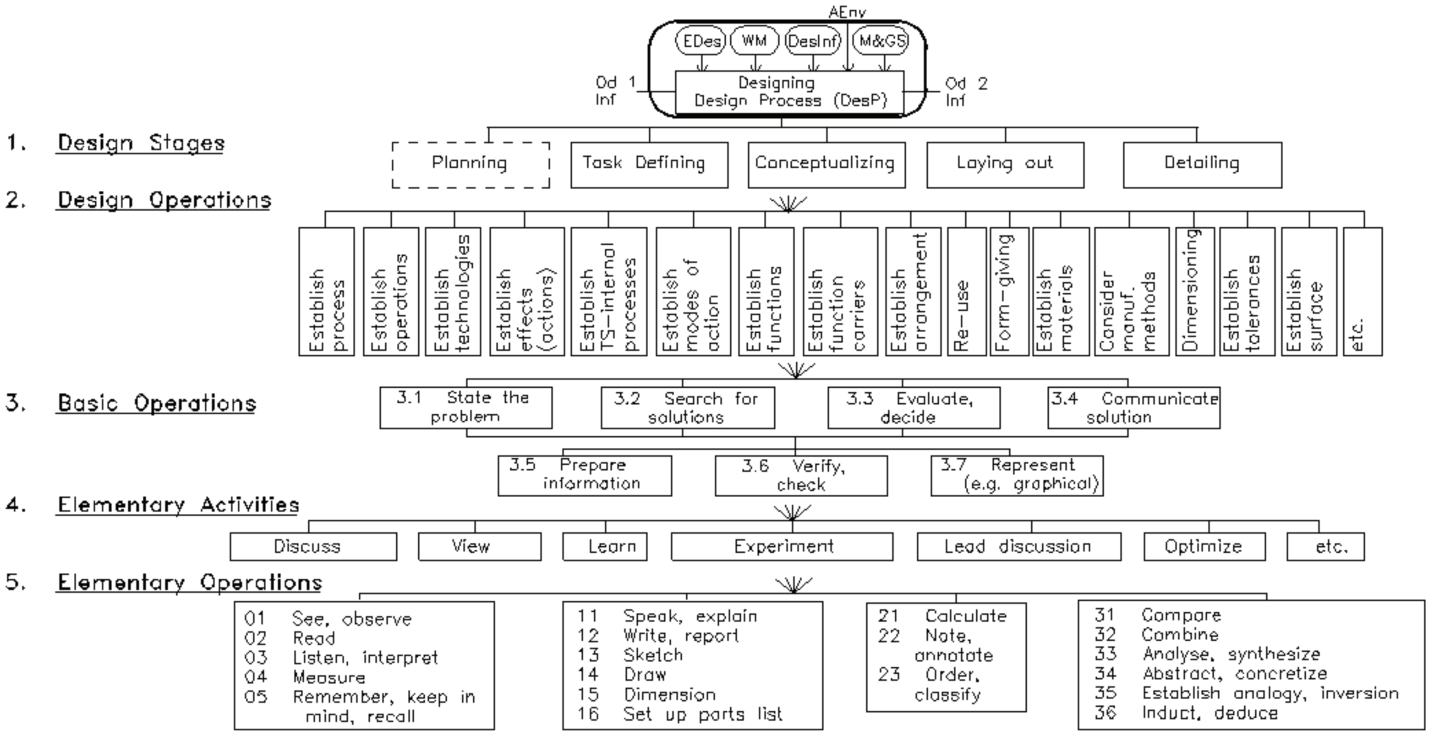
## 2.2 Research framework of the study

The mechanical engineering design student is generally the first and foremost recipient of new methods that concern the design process. It is necessary to know what the student knows and does not know in order to help him/her. In industry, two categories of designers can be considered: the engineer who has less than 10 years of experience in mechanical engineering design, and the expert who has more than 10 years of experience. The designation of 10 years as separating the expert from other categories has been assessed from cognitive studies (see Kellogg 1995, p. 226). Observations of the design process are thus dependent on these three levels of expertise: student (novice), designer (intermediate — experience inferior to 10 years) and expert.

In order to obtain useful results that are not redundant and to organize the observation results, there is a need to clarify which elements of the design activity need to be studied and to organize them into a structure. The design activity can also be considered within different granularity levels. Developed iteratively with the study of both the literature and the observations of designers at work, the design activity has been decomposed in 4 levels:

1. the designer placed in his or her daily work environment;
2. the tactics and strategies applied during the whole embodiment and detail design activities;
3. the operational, cognitive activities during design, especially problem solving;
4. the basic cognitive elements: induction, deduction, abstraction, perception, pattern recognition, attention, intelligence, etc.

The design activity can be seen as an *action* in an *environment* for a *project*, which corresponds relatively well to the definition of a system by Le Moigne (1990, p. 40). Thus the design activity can be considered in a system perspective, wherein the individual designer is the control, information processing and operative units simultaneously, and acts in a work environment. The environment includes the product development team, the external tools, methods and techniques the designer has at his/her disposal, and the company as a place of work and of culture that influences the designer's work. The designer's work environment forms the first level of the four-level study model. PSP is often presented as the basic operations in design. Following Hubka's structural model of design (1980, p. 20; see also Hubka & Eder 1996, p. 135), presented in Figure 2.1, the problem solving activities were then subordinated to the design activities, and regrouped with other basic activities such as those involving visualization, use of external support system, knowledge, etc. under the denomination of *design operations and skills*. The design activities, used in different strategies and tactics form the second level of the four-level study model, and the basic operations the third level. Basic cognitive elements such as induction, deduction, abstraction, and pattern recognition are said to be constitutive of the PSP, both from a cognitive psychology point of view (see Sternberg 1994) and from that of the field of design research (Hubka & Eder 1996, pp. 133-135). These elements have been used directly in some design studies: Lin & Wang (2001) studied abduction in an industrial design problem; Kavakli & Gero (2001; 2002) analyzed sketches as mental imagery processes and as a part of concurrent cognitive actions. The study of these elements seemed to be on a too detailed level to be considered for the research project. The hypothesis is made that the study of their articulation will give little information on how the designer performs synthesis, so the fourth level is not included in this study. The four-level study model of the designer's activity is presented in Figure 2.2.



**Relationships:**

A. hierarchical -- every activity at one level (e.g. '3.6 Verify, check') contains the activities at the next lower level (e.g. 'Learn'), and is simultaneously contained in every activity at the next higher level (e.g. 'Form-giving');

B. black dependency -- some activities are repeatedly applied in a certain (flexible) sequence, particularly the cycle of problem-solving operations at level 3 Basic Operations.

Note: 'thinking' is not included in this hierarchy, this process takes place inside the human and is not directly observable or verifiable by documentation (e.g. written or graphical records). Thinking could be incuded at level 4 Elementary Activities.

Figure 2.1 Structural model of the design process (Hubka & Eder 1996, p. 135)

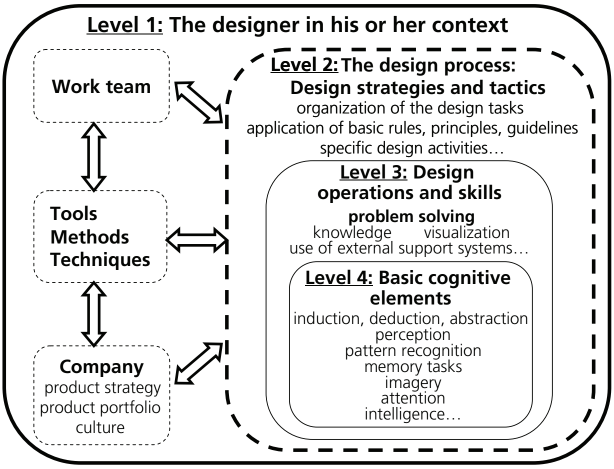


Figure 2.2 The four-level study model of the designer's activity

For the first step of this research study, observations of how the designer performs synthesis in the later phases of the design process, 9 cases are to be studied (3 of the 4 levels of the design activity, 3 expertise levels, only individual designers and only one type of embodiment design and detail design problem). At level 3, only the design operations (PSP) have been studied. As the study of the mechanical engineering student in its environment is not relevant, the number of cases is down to 8. The 4 cases framed in Table 2.2 are the ones that have been studied so far and that are reported in this thesis.

Table 2.2. Study cases of synthesis

| | *Student* | *Designer* | *Expert* |
|---|---|---|---|
| *Level 1* | / | ✓ | ✓ |
| *Level 2* | ✓ | ✓ | ✓ |
| *Level 3 (PSP)* | ✓ | ✓ | ✓ |
| *Level 4* | / | / | / |

## 2.3 Research strategy and process

The research strategy adopted is a rather loose one. The goal is to gain knowledge of designer actions, causes of action and mistakes in order to contribute later on to the development of a methodology for the later phases of the design process. Following the pragmatic approach and framework described above, the research process has been the following:

1. Extensive literature study — became the object of Paper A. Originally, the focus was on the cognitive aspects of design, which is why this literature study deals only with this perspective.

2. Elaboration of an experimental protocol and execution of six experiments with 3 students and 3 experts. First analysis of the design process at the PSP level — presented in (Motte et al. 2004).
3. Development of the four-level study model of the designer's activity.
4. Analysis of the design strategies and tactics — presented in Paper C.
5. Refinement of the analysis of the design process at the PSP level — presented in Paper B.
6. The students are without doubt the designers who are the most likely to learn any new (or improved) design methodologies, even if they are meant primarily for the practitioner. The experienced designers may encounter new design techniques and tools, but it is likely that few of them will try actively to change their current practice. Thus the students are directly affected by the development of a new design methodology. The study of what they know before the course and after the course was the object of a fourth analysis — presented in Paper D.

The next steps of the project are presented in Section 6.1 Towards the completion of the *overall* research project

## 2.4 The experimental method

The method chosen is the one most used in the framework of the observation of the designer at levels 2 and 3 of the four-level design process model: observation of the designer under a controlled experiment where the designer is asked to "think aloud" and whose verbal protocol is analyzed by means of a set of categories representing basic activity moments. The method is described in the first section; the experimental procedure is presented in the second section. Sketches were also analyzed (Section 2.4.3) in a very restricted way; hence no particular method was employed.

### *2.4.1 Verbal protocol analysis*

Ericsson & Simon (1993) are the original disseminators of this method. The pros and cons, as well as the techniques for protocol analysis, are described in depth in their work *Protocol Analysis*.

The participant in such an experiment is asked to "think aloud" during the whole time of the experiment and his "thinking aloud" is recorded. He is expected to say what he is doing, not what he plans to do and not to reflect on what he did. It just takes longer to perform a task due to the time used for this kind of verbalization, so the only theoretical bias is that the design task will be performed somewhat more slowly (Ericsson & Simon 1993, p. xix-xxii). Only verbalizations like *explanation* or *judgment* influence the performance, as compared to a silent condition (Ericsson & Simon 1993, p. xviii). The verbalizations are not the description of the cognitive processes behind the action; they are rather a result of their application. It is up to the analyst to develop a process model that can explain the results obtained.

The method for protocol analysis proposed by Ericsson & Simon (1993) is the following:

- The participant's verbalization is transcribed, and the problem solving process and protocol are analyzed to extract the vocabulary of objects and relations needed to define the problem space and operators.
- The protocol is then segmented, each segment corresponding to a statement. The list of actions used to encode the segments can be extracted from the elicited vocabulary or from a pre-determined coding scheme.
- There can be several levels of analysis. The episodes can be aggregated (which is often the case in design studies), for example, or the actions.
- In order to ensure reliability, the coding should be done by two coders independently.

At the beginning of the experiment, in order to train the participant to "speak aloud", a small exercise with no link to the object of the experiment is presented.

In the field of design research, the first step, extraction of the vocabulary, is often skipped, or not reported in the publications. Beyond that point there has been little adaptation of this method for the field of design research; the method has often been adopted as is. This lack of adaptation has generated some criticisms; Davies (1995), for example, draws attention to the fact that the protocol analysis method has been developed for well defined problems and short tasks (resolution of an equation for example), and may not be adaptable for design problems. Moreover, the participant is in this case put in an emotionally loaded situation. Designing is what the participant is doing (or will do) for a living, and it is his competences and skills that are at stake. The participant performs an activity that will be analyzed and dissected by a panel of experts, and this puts him under huge pressure. It is not at all sure whether the designer will act "naturally", following his usual practice. It is also possible that the designer will try to justify his choices and reflect over his actions, which will lead to an inferior performance. Finally, Davies (1995) doubts that the verbal protocol alone gives a complete picture of the design process. Indeed, the designer also communicates with the help of sketches, for example. Different modes of expression are possible, and each reveals a part of the design process. An example of multimodal analysis of a design process (based on vocal, graphical and gestural activity) is presented in Leclercq et al. (2004).

Some researchers have proposed that two designers co-operating to solve a common design task would provide a more natural setup (e.g. Shah et al. 1993). It is true that the designers are then relieved from most of the pressure and are focusing more on the task, but the observation of two designers together does not fulfill to the same purpose as the observation of a designer alone. It gives some insight into how two designers collaborate, but does not reflect the design process of one individual designer.

### 2.4.2 The experimental procedure

This section is mainly taken from (Motte et al. 2004).

#### 2.4.2.1 Setup of the experiments

The subjects selected for the experiments were three students and three experts. The three students all came from Lund University, and had followed the product development/mechanical design syllabus. Two students were seniors, one was a junior. The junior was about to begin the course on form design, while the two seniors were completing their Master's theses. All the experts had more than 20 years' experience. One had always worked in industry, one always in academia, while the third had worked half in industry, half in academia.

The experiment, for each of the subjects, lasted two hours and was organized as follows. Each experiment took place in an isolated room. The subject was face-to-face with an experimenter. To the left of the subject, a video camera, operated by a second experimenter, recorded the sequence, following the focus and the actions of the subject.

Based on the ethical principles employed in the sociological and psychological fields of research, a secrecy agreement was co-signed by each of the subjects and experimenters. This protected the subjects from being identified by a third party, but allowed any researcher who would like to question the results to have access to the tapes, assuming the signature of a new secrecy agreement. Such a procedure guaranteed the integrity of the subjects without hindering the research process.

At the beginning of the experiment, the subjects were given a short exercise in order to practice thinking aloud. This exercise was the so-called "Missionaries and cannibals problem", classically used in cognitive psychology. The subjects did not have to solve it, and their ability to work on this exercise was not taken into account for further analysis. Then the mission statement was delivered to the designer.

The subject was asked to design and dimension a support for a hydraulic piston that had to be fixed to the ground. The piston, guided laterally, took an axial force of 90 kN. Under the piston, an installation was located on the ground. The support was to stand beside this installation (see Figure 2.3). The specifications of the piston were given in the assignment. This design task was relatively well defined, and corresponded to what one can expect from a similar situation in an industrial project. The assignment has most of the characteristics of an embodiment and detail design task, in the sense that the designer has "to fulfill a given function with appropriate layout, component shapes and materials" (Pahl & Beitz 1996, p. 205), and it takes into account most of the factors affecting embodiment design and detail design phases listed in Pahl & Beitz (see Table 2 in Paper C). Intentionally, the form-giving aspect was not very complex, so that the subjects had time for dimensioning. Finally, there was a short interview in which the subjects were asked to evaluate their design and the experiment.

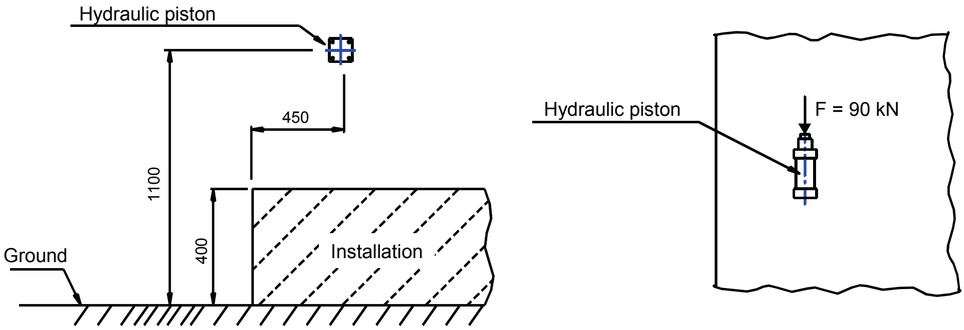


Figure 2.3 Sketch of the problem delivered with the assignment

### 2.4.2.2 Setup of the coding schemes and analysis

*2.4.2.2.1 Specificities of embodiment design and detail design*

While novelty and creativity are emphasized during the conceptual design phase, the embodiment design and detail design phases focus on the rigorous study of all elements of the problem and their interrelations, and on the combination, or composition of sub-solutions, to create an overall functioning system (synthesis). This indicates that the ability and experiences required in problem solving can differ between embodiment/detail design and conceptual design.

From these considerations, and after the survey of the relevant papers referenced in Paper A, the coding schemes developed for conceptual design that had been studied (Atman et al. 1999; Ball et al. 1998; Purcell & Gero 1998) were considered as unsuitable. New coding schemes were then elaborated for each of the partial studies: PSP, tactics and strategies. In order to find new coding schemes, the first experiments were analyzed by decomposition of different segments of thoughts. In order not to "stick" with the existing coding schemes (the human limitations observed for the designers apply as well to scientists), another researcher (Per-Erik Andersson) participated in their elaboration. The actions (categories) of the PSP were considered as the first level of analysis, tactics and strategy as an aggregated level of analysis.

The coding scheme elaborated for the PSP study aimed at getting a description of synthesis as a generative activity, and at closely analyzing the activities of information search and evaluation/decision-making. The coding schemes elaborated for the study of the strategies and tactics developed by the designers were based on the basic design tasks found in the literature and through observations of the designers. The description of the PSP coding scheme can be found in Paper B and that of the strategies and tactics coding schemes in Paper C.

*2.4.2.2.2 The protocol analysis process*

Sometimes the analysis is made by two researchers independently; then the results are compared and a final protocol analysis is realized (e.g. Atman et al. 1999). However, as this coding scheme was new, it was decided to have the protocol analyzed by both analysts together. The decision of one analyst should be accepted by the other in order to carry on the analysis. Thus the analysts, after the first coding experiment, had the same pattern of thoughts concerning the whole coding process.

### 2.4.3 Analysis of sketches

No particular method was employed while analyzing sketches. What was studied was mainly the degree of abstraction of the sketches and their impact on the design process. Whether the designer used standard parts or created unique parts was also studied. In Paper D, which focused on the comparison between juniors and seniors, sketches of students that carried out the design assignment as an examination task were also analyzed.

# 3 Frame of reference

*This chapter positions this thesis in its theoretical context by presenting the elements employed from the literature: current prescriptive design methodologies and works that claim for a more designer-centric development of design methodologies.*

*The design methodologies of VDI Guideline 2221 (1987) and Pahl & Beitz (1996) served as the main points of departure. The design methodology proposed by VDI Guideline 2223 (2004) is also described. Existing support tools that can aid the different activities of synthesis are only briefly introduced: they have not been utilized in this study because the thesis focuses solely on the designer's know-how. Many research works have pointed out the weaknesses of these prescriptive methods. A review of these reflections is followed by a literature review on the cognitive aspects of design, presented in its entirety in Paper A*[4]*. This review is also completed by new elements that came to the author's knowledge after the publication of Paper A.*

*Prior to an elaboration of the literature elements referred to above, some basic observations about the concept of design are introduced to provide a theoretical context for the findings of the thesis: the definitions of the mechanical engineering design and the mechanical engineering design process that applies to this thesis, the place of the design activity in an industrial environment, and the hypotheses that lie behind the design methodologies employed.*

## 3.1 Basics of design

### 3.1.1 Definitions

The terms "design" and "design process" have raised many passions and contributed to stormy discussions about their nature. Even the more restricted expressions "mechanical engineering design" and "mechanical engineering design process", concerning only mechanical engineering-related design activities, has its own ambiguousness. Every author has his own definition: Olsson (Olsson 1976, pp. 37-39) pointed to 16 definitions of engineering design, concluding that it was impossible to make a synthesis from them and that they could only be used as a background for his thesis. It is claimed that the irregularities of a design sketch help the designer to discover new potential improvements to his/her solution (Kavakli & Gero 2001); analogously, only a sketch of the definitions is given, providing the reader freedom to adapt these

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[4] The summary of Paper A is to be found in Chapter 4, together with the summaries of the other appended papers.

expressions to the context of this work. The definitions[5] below will be relatively concrete, as the ultimate object of the *overall* research project is the support of the design activity in industry and its teaching.

MECHANICAL ENGINEERING DESIGN: Constitutes that field of engineering design whose purpose is to deal with those products or parts of products in which the working principles are based on the laws of mechanics.

MECHANICAL ENGINEERING DESIGN PROCESS: Comprises all the activities related to mechanical engineering that aim at developing a product from the perceived need to the necessary technical documentation required for production.

### *3.1.2 The design process as a part of the product and technology development processes*

The design process is one part of a whole product development process. Figure 3.1 presents a model of a product development process from the former Swedish Society of Mechanical Engineers (Sveriges Mekanförbund 1985)[6]. Throughout the development of the product, the designer co-operates with other members of the product development team who belong to other areas of engineering and other functions of the company. This cross-functional cooperation influencing the first level of the four-level model of the designer's activity (Figure 2.2, p. 11) is also not a part of the presented project.

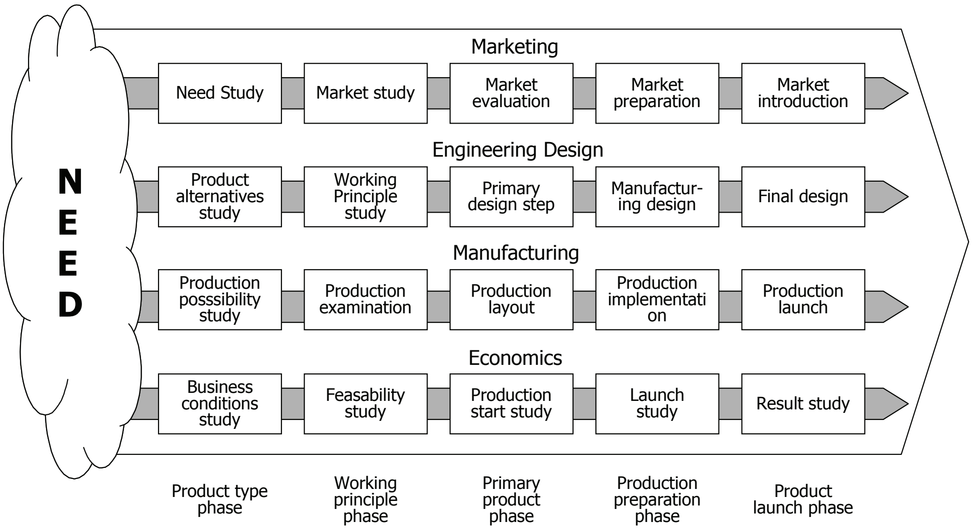

Figure 3.1 Integrated product development (from Olsson in Sveriges Mekanförbund 1985)

But, moreover, the design process can be a part of a technology development process. This has been seldom taken into account in the literature, which almost always

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[5] The following definitions have been elaborated together with Prof. Robert Bjärnemo. A glossary at the end of this document reproduces the definitions of the main terms employed in this thesis.

[6] Prof. Fredy Olsson, Machine Design, Lund University, was the main contributor.

defines the design process in relation to the product development process. This has several implications, in particular concerning the conceptual design phase. In highly competitive sectors like the automotive industry, failures cannot be tolerated. It must be ensured that a product will be developed within a given time and at a certain cost. Thus there is little room for uncertainty. The development of new systems or components is performed within the research departments, while product development aims at adapting these new technologies to the new car to be developed. It is not sure whether the current mechanical engineering design process models (such as those described Section 3.2) are adapted to technology development. The embodiment design and detail design activities as a part of a technology development project has not been considered in this thesis.

### 3.1.3 Modeling the design activity

This section describes how this thesis is positioned in relation to the different approaches of modeling in engineering design.

There are many ways to model the design activity and as many ways to classify these approaches (see Wynn & Clarkson 2005 for the most recent review to date on this subject). Lonchampt (2004) proposes a classification of different design modeling approaches that is interesting because each approach basically corresponds to a different purpose. This classification has been adopted here:

- The phase-based modeling approach
- The activity-based modeling approach
- The domain-based modeling approach

The models based on a process model decomposed into phases or stages (themselves decomposed into steps) are concrete and have a practical purpose. The most recent models are all a part of a whole design methodology, which means that for each step one or several *methods* (and/or *tools*) are affected, which will concretely show to the designer how to fulfill the step (Bjärnemo 1983). Some examples of design methodologies are, among others, Pahl & Beitz (1996), Ullman (1997), Pugh (1990), VDI Guideline 2221 “Systematic Approach to the Design of Technical Systems and Products” (1987), VDI Guideline 2222 Part 1 “Conceptualizing Technical Products” (1977) and VDI Guideline 2223 “Systematic Embodiment Design of Technical Products” (2004). The methodology presented by Ulrich & Eppinger (2003) is more dedicated to product development than to design. The sequencing of the phases or steps of the design process is general and is meant to be used as a plan or strategy to be followed during the design of the TS. It describes the design process along the temporal dimension. The *methods* are to be used within one step at an operational level by the designer. If the different steps of a process tell the designer “what” to do, the “method” indicates “how” to do it. The design *tools* are meant to assist the designer in performing his/her activity. Some specific tools for synthesis are presented in Section 3.2.5. The German methodologies (and Olsson 1976) are moreover based on the theory that the design activity is a problem to be solved. Thus the design process model becomes based on a generic PSP (see next section). The methods themselves are also based on this generic PSP or heuristics. A grounded methodology at least permits guaranteeing that the methodology has internal coherence and internal validity. Anglo-Saxon methodologies (Suh 1990 excluded) are more generally based on "best practices" (see Ullman 1997). Underlying influences of design methodologies are systems theory and formalism to help in modeling both the product and the process, the hypotheses that the process model has to be organized towards the continuous refinement of the product-to-be, and that the output of the different steps will be optimal if the method applied has a systematic nature.

The activity-based modeling approach is characteristic of descriptive studies of the design process. The observed designer's process is modeled in a detailed way, taking into account cognitive, social and emotional aspects. The activity-based models can also be used and developed as coding schemes for verbal protocol analysis, which provides the discovery of design process characteristics that should be taken into account for serving as a basis for improvement or development of design support in whatever form it may take. See Lonchampt (2004, pp. 61 ff) for some examples of activity-based models. It can be noticed that the activity models found in the literature are also based on the implicit theory that the design activity is a PSP. To the author, very few results based on these models have been implemented later into some sort of help for the designer. Lambell et al. (2000) developed an expert system prototype for design support. Findings from these descriptive models are gradually taken into account in the more prescriptive methodologies, but not really integrated. In the third German edition of Pahl & Beitz's *Engineering Design – A Systematic Approach* (1993), a "psychology of problem solving" section was added, but the design methodology has remained unchanged since the first edition (1977). In VDI Guideline 2223 "Systematic Embodiment Design of Technical Products" (2004) the designer's skill and "cognitive limitations" are taken into account for the application of the methodology.

The third approach can be considered as a way modeling that is the dualism of the first two approaches. The phase-based and the activity-based modeling approaches focus on the actions for the designer to take; the domain-based modeling approach is concerned primarily with the state of the design (the result of the design activity) at a given moment. Some domain-based models are discussed in Lonchampt (2004, pp. 67 ff) and Hatchuel & Weil (2003). Many of them are intended to contribute to the development of a theory of design. Among them, the C-K theory (see next section) is interesting because it considers the design activity as a production of knowledge rather than a problem to solve. This can open new ways of developing support for the designers, or improving existing ones.

Heretofore, there have been two ways to design: by applying a design methodology or by trusting one's competences, knowledge and intuition and using specific design techniques when needed. For many concrete design problems, it is not sure which one of these ways is preferable. Pahl (1983) reports cases where the use of a systematic methodology is superior, while Bender (2004) questions this result. There are reservations about the existing methodologies, but the concept of methodology itself (general phase-based design process, methods and tools) is not questioned. It is still believed that it is possible to find a more effective design process than the intuitive one. The outcome of the *overall* research project (a support for synthesis at the embodiment design and detail design phases) is also to be methodological in nature, using the phase-based modeling approach in a perhaps more flexible way. This thesis, however, is concerned with the design process at the activity level. The second approach will be used as a foundation for modeling and analyzing the design activity at levels 2 and 3 of the four-level study model. The C-K theory might lead to a third way of considering the act of designing, but this theory is still in its infancy and is not advanced enough to be taken into consideration in this study.

The assumptions behind the structure of the methodologies used as starting points are presented in the remainder of this chapter. The methodologies themselves are presented in Section 3.2; their limitations and the more designer-centric approaches to the practice of design are in turn presented in Section 3.3.

### 3.1.4 The design process as a problem-solving process[7]

The design process models mostly taught and employed nowadays (e.g. Pahl & Beitz 1996; VDI Guideline 2221 1987) are basically considering the design activity as a problem to solve. There are different variants, but all problem-solving process (PSP) models can be described by Simon's (1961) generic model presented below.

A problem is a gap between an Observed State ($S_o$) and a Desired State ($S_d$), $S_o \neq S_d$, given a set of constraints. The procedure to apply in order to get to the desired state may be unknown; $S_o$ and $S_d$ may need to be refined and can change over time. Simon's PSP Model is a three-stage model (Figure 3.2):

1. INTELLIGENCE to understand $S_o$, $S_d$, the constraints and define them
2. DESIGN to generate solutions
3. SELECTION to decide:
    - to redefine the problem (back to *intelligence*)
    - to refine or find new solutions (back to *design*)
    - to choose one solution

The next step is implementation of the solution. This process model is recursive. For example, *Intelligence* can be decomposed in a new PSP: intelligence of the situation (find $S_o$, $S_d$ and the constraints), generations of different problem definitions, choice of one. Moreover a problem can be decomposed into sub-problems. Within each stage, a procedure can be used, either algorithmic in nature (leading automatically to a solution) or heuristic (known procedure that gave the best results for a specific problem).

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[7] Only the elements used in this study have been presented here. For a review of the state-of-the-art on problem solving in design, see Visser (2004).

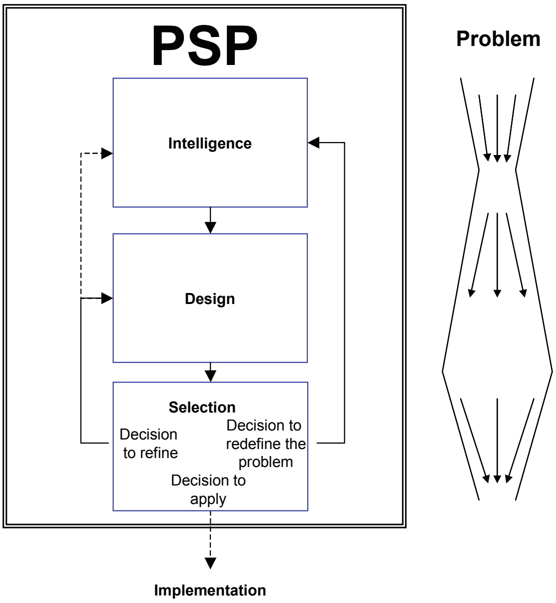

Figure 3.2 Problem-solving process (from Simon 1961)

The current design process models employ the term *State the Problem* or *Clarify the Problem* (Ehrlenspiel 1995, p. 79; Hubka & Eder 1996, p. 135) instead of *Intelligence*, and *Search for Solutions* instead of *Design*. Simon's model is preferred because it infers that the problem solver has to *understand* the problem in all its complexity rather than just analyze, formulate and structure it (as in Ehrlenspiel 1995, pp.79-80). The fact that Simon calls the second phase "design" recalls the true nature of design: creation and generation of new solutions, which differs from other types of problems. To Simon's mind, design was slightly different from problem solving, even if this position would later change, as he tried to develop a unified method of problem solving (see *The Sciences of the Artificial* 1969; and also Simon 1973). These differences allow more flexibility in the adaptation of this generic PSP to particular situations. This model was also used as an inspiration for the study of the embodiment design and detail design phases.

It is interesting to notice that design was not considered as such in earlier literature, and that this view is currently being challenged. Even Jones (1962), who early claimed for the use of a systematic design method and whose method (*Analysis*, *Synthesis* and *Evaluation*) was based on the same principles as the former generic problem-solving process and recalls Polya's (1957) model of the mathematical problem-solving process (which was also based on the *Analysis* and *Synthesis* phases), did not explicitly refer to the design activity as a problem to solve. A view challenging the design activity as a problem to solve can be found in Hatchuel & Weil (2003), who present the design activity as a production of knowledge. This idea, first developed by Simon (1969), shifts the view of design and permits elaborating new types of design process models. The philosophy of the C-K theory is to consider that there exist two domains: the domain of knowledge (internal to the designer, and external, concerning the product or process…), and the domain of concepts. A concept is an element whose logical status is not known (to know the logical status of an element is to know if this element is true or false, for example), while knowledge is an element whose logical status is known. Designing is transforming a concept into knowledge. Considering the design activity as a problem to solve links the activity of design with activity domains like chess playing or logic. Considering it as creation of knowledge is linking it to science or art, which opens up new thinking patterns. This view has not been taken into account in this thesis, as this theory is still embryonic in nature, and did not correspond to the traditional models and methods of design which are employed in this study, namely Pahl & Beitz (1996) and the VDI Guidelines 2221 (1987), 2222 (1977) and 2223 (2004).

The presentation of the design process as a PSP was in all likelihood first done by Krick (1969). This has been subsequently developed and employed in the references mentioned at the end of the previous paragraph. A full description is available in Ehrlenspiel (1995).

The strength of a PSP model is that it can describe the design process at several levels, because of its recursivity: strategic (the whole process), tactical or operational. It can be used both to analyze a normative, prescriptive model and a descriptive model, and to serve as a basis for developing them. If some PSP steps are missing in a design process, for example, this is a good indicator of possible failures in the process. Beyond that aspect, PSP models also present weaknesses: they are heuristic in nature, and one could even say that they are "weak" heuristics (Schregenberger 1985). They do not at all ensure a good result while following these steps. More amazingly, according to Lipshitz & Bar-Ilan (1996), no empirical studies were found that could determine whether a PSP model needed to be sequential in nature, or could show that one PSP model variant (which consists generally in renaming the generic steps or adding some moments to them) was better than another. It was also still not shown whether this process was a "natural one" or not. This can question the PSP as an adequate model for the design process, but it is still a powerful model generally accepted, and it can be one good way to compare one's observations or modeling to others'.

### 3.1.5 The design process, based on system formalism and theory

A general system, be it a biological one, an organizational one or a technical one, is described by an *action* in an *environment* for a *project*, *transforming* itself by *functioning* (Le Moigne 1990, p. 40). Mechanical products have long been modeled as systems functioning in an environment, transforming energy, material and/or signals. The "black box" is a general representation formalism of the functioning of the product. Hubka, who developed the concept of technical systems (Hubka 1973), represented the design process with the same formalism (Hubka 1976), and has integrated both the design process and the working process of the TS as "black boxes" of the TS life cycle (Hubka 1980; 1982). This gives a coherent but nevertheless only descriptive and highly abstract perspective of both processes — see Figure 3.3.

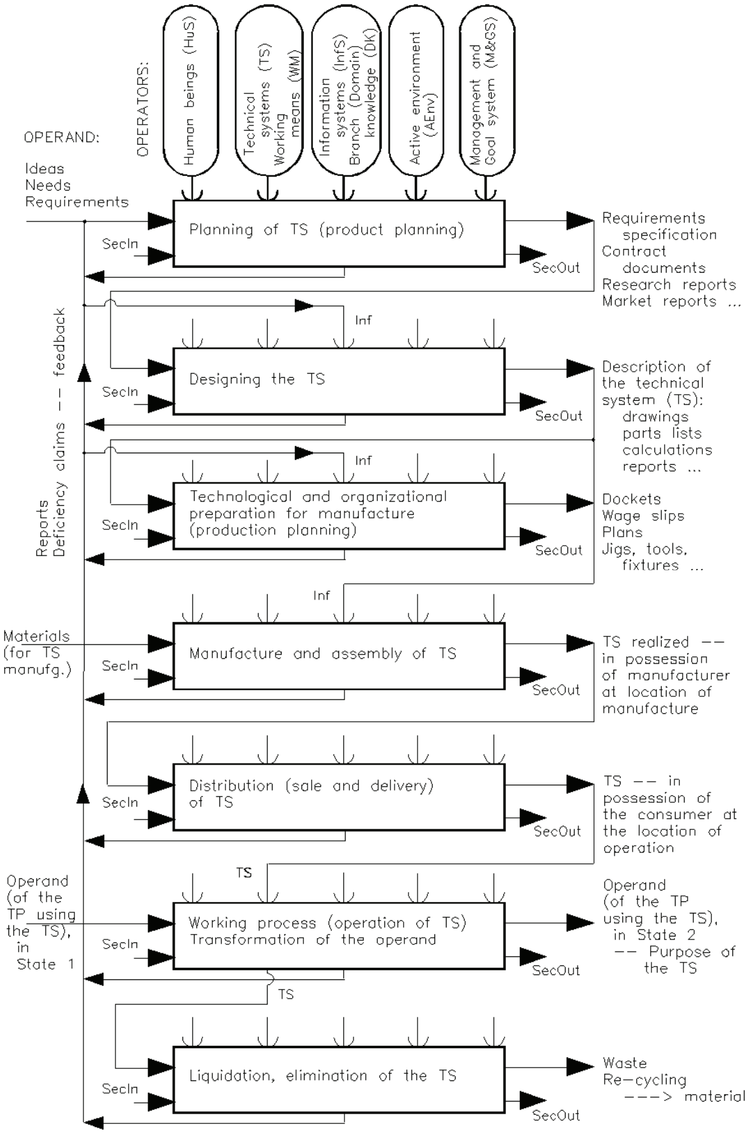

Figure 3.3 Life Cycle of Technical Systems (Hubka & Eder 1996, p. 122)

### *3.1.6 The design process, based on a continuous refinement of the product and other constraints*

A constraint, implicit in the design process models presented in the literature is that the design process must be based on continuous refinement of the product. As French (1985, p. 1) puts it: "Ideally the intervening stages [for the design of a product] should be of successively increasing precision, of gradual crystallization or hardening". Hubka (Hubka 1982) as well developed this idea (see Figure 3.4). It is also one part of the definition of Pugh's total design model (see Pugh 1990, pp. 5-7).

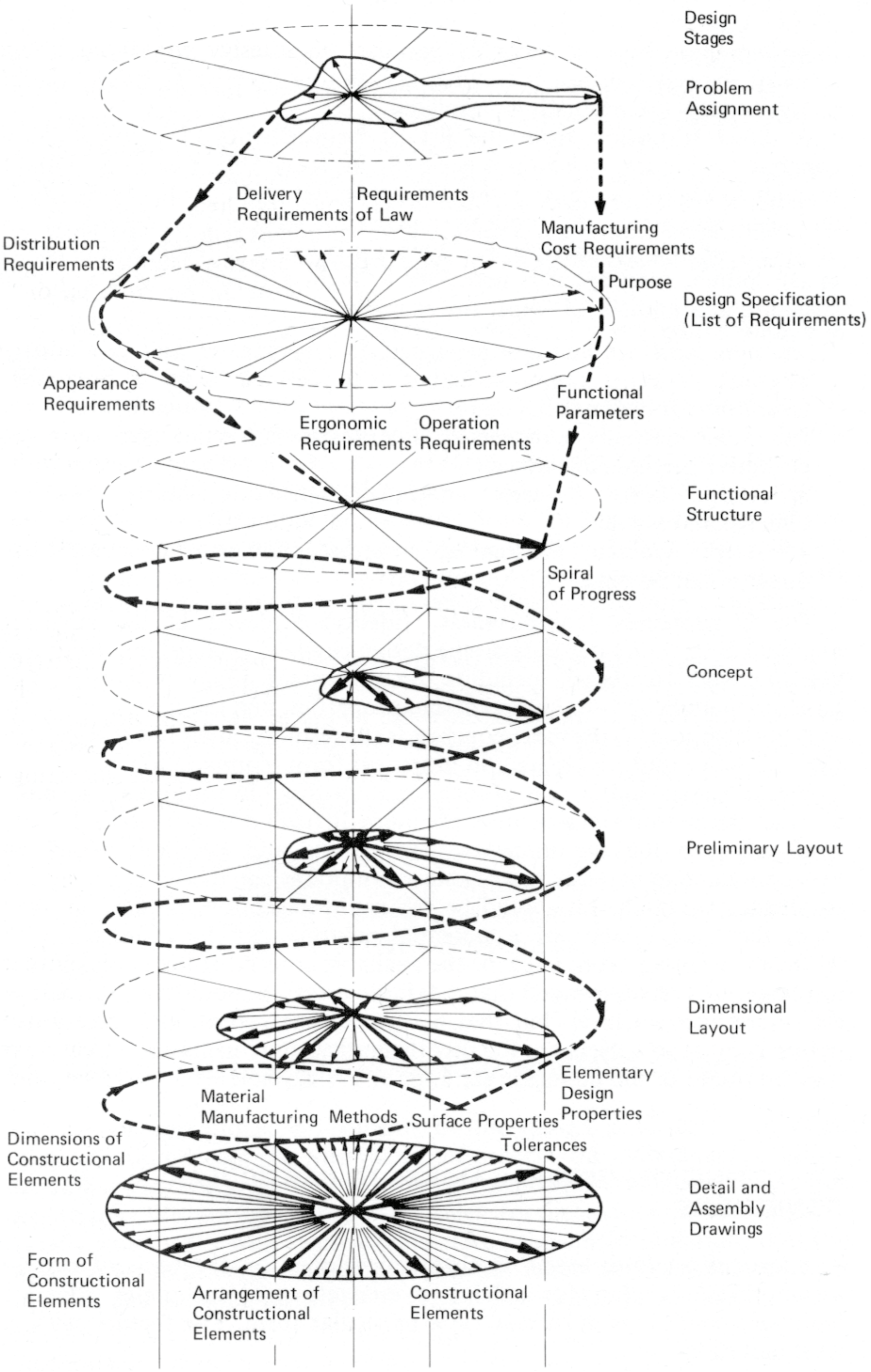

Figure 3.4 Degree of completeness of the TS properties along the design process (Hubka 1982, p. 35)

Some tasks are not undertaken before the end of the design process for purely logical reasons (some elements cannot be determined before others), but some are postponed due to this implicit constraint, which explains some apparent lack of flexibility of the structure of the current design process models.

Finally, one heuristic emphasized by prescriptive design methodologies is that the methods related to each step should be systematic in nature in order to obtain an optimal result.

## 3.2 Mechanical engineering design process methodologies

In Section 1.2, the mechanical engineering design process has been presented as consisting of two parts: the conceptual design phase and the embodiment design and detail design phases. This has been done more for the sake of simplicity of surveying the situation than for theoretical reasons. All the current well-known design process models are decomposed into more phases, but since upstream phase decomposition of the design process including conceptual design is beyond the scope of this study, and downstream decomposition (e.g. separation between embodiment design and detail design) differs from author to author, the upstream phase decomposition is denoted as the *conceptual design phase* and the downstream phase decomposition as the *embodiment design and detail design phases*. It has been chosen, with reference to the goal of the study, not to make any separation of the sub-problems constituting these later phases of the design process. This means that these phases, even though terminologically referred to as two phases, are here treated as one. The borderline between the conceptual design phase and the later phases is clearer, though some differences between models exist. Depending on where this boundary is laid between the conceptual phase and the embodiment design and detail design phases in the literature, this study can also apply on some conceptual design tasks.

The conceptual design phase is by nature the phase whose output is a product concept. Nevertheless, as mentioned above, “the elusive concept of concept” (Heylighen & Martin 2004) can make it difficult to define the scope of this study. In order to clarify this problem, a complete mechanical engineering design process is presented. This will also make the starting and finishing conditions of the embodiment design and detail design phases more apparent, and will help position this study. Two embodiment design and detail design process models are then reviewed in detail: Pahl & Beitz’s (1996) model, which was the starting point of this study, and VDI Guideline 2223 (2004) model. This guideline presents the position of the German industry towards, and recommendations for, the embodiment design phase. Finally, in order to complete this general view, the tools that support synthesis are introduced at the end of this section.

### *3.2.1 General design process model*

Many reviews of the mechanical engineering design process models already exist: Bender (2004) and Lonchampt (2004) for the most recent ones; Pahl & Beitz (1996) summarize the German research work on this area; Hubka (1996) the whole world; for a comprehensive review of older mechanical engineering design process models, see also Bjärnemo (1983). The *current* mechanical engineering design process models are relatively similar, making it possible to present but one general approach.

The presentation of VDI Guideline 2221 (1987) is a good starting point as it is a compromise among the German schools of mechanical engineering design. Indeed, most of the members of the committee have delivered important contributions in this field: Prof. Beitz — chairman of the committee, Prof. Pahl, Prof. Ehrlenspiel (1985; 1995), and Prof. Roth (1982), among others.

A majority of the actual design process models follow a systems approach: a certain number of steps, often called stages or phases, which need to be performed, and whose results determine the passage to the next step. As each result of one step can influence the results of an earlier step, the process is iterative. VDI Guideline 2221 defines the concrete use of stages and phases: “Depending on the task, either all the stages are completed or only some, with stages being repeated as necessary. In practice, individual stages are often combined into design phases, which assist the overall planning of the design process. Such a combination into phases can differ depending on the branch of industry or company, and also according to the concepts involved.” (VDI Guideline 2223 1987, p. 7)

Figure 3.5 shows the general approach of VDI Guideline 2221. The figure illustrates the quotation above: the phases are overlapping. For the mechanical engineering design process, these four phases are (VDI Guideline 2223 1987, p. 12):

I. clarification of the task

II. conceptual design

III. embodiment design

IV. detail design

According to this general approach, a design process will be efficient if the product is first described in term of a structure of technical functions (with inputs and outputs determined as energy, material and signal) that fulfills the need perceived by the market (stages 1 and 2). If in-house or commercially available solutions to the sub-functions do not exist, physical effects need to be searched. These physical effects are then *realized* by their geometry and motions and by selecting materials (embodiment features), denoted solution principles[8]. The solution principles must in turn be combined according to the function structure to form concepts (stage 3).

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[8] The solution principles of sub-functions can be also called *function carriers*. Pahl & Beitz (1996) call the combination of a physical effect together with geometry and material for *working principle*. The difference between a working principle and a solution principle is that the working principle is an abstract solution that work for a given function but needs to be further adapted to the particular product so that the solution can be assessed against criteria. This can involve preliminary dimensioning and scaling or deeper analyses: the result is thus the solution principle.

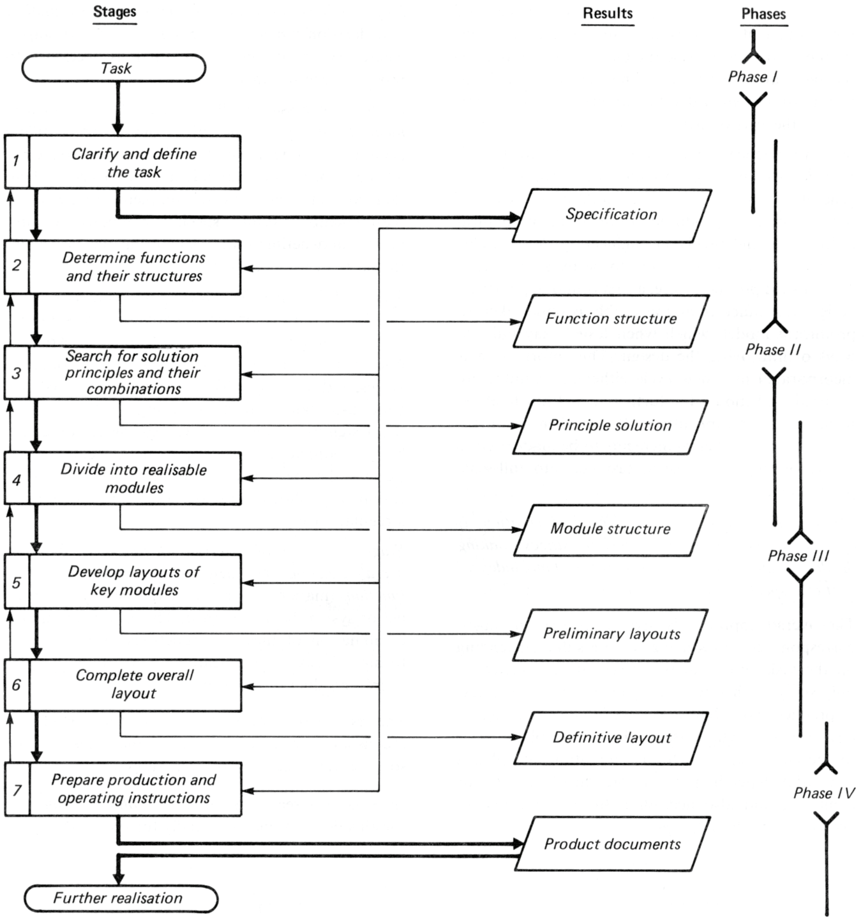

Figure 3.5 General approach to design (VDI Guideline 2221 1987, p. 8)

In VDI Guideline 2221 (1987, p. 13), the embodiment design in mechanical engineering design is composed of stages 4 to 6, and the detail design phase corresponds to stage 7. Once one concept has been chosen, it is structured into assemblies and parts (stage 4). This stage concerns also the establishment of the product architecture (or product layout). This means that spatial arrangements and interfaces are fixed at this stage. Solution principles for auxiliary function carriers (e.g. support or protection structure) are then determined. Joints and fixtures are established, as well as materials and manufacturing methods. Standard components are sought (stage 5). Stage 6 is the completing stage: joints are fully dimensioned; all missing dimensions are set up; tolerances, surface finishes and material treatments are determined; Design for X activities are performed. Lastly, the final documents for the manufacture and operation of the technical system are produced (stage 7).

Among the tasks of embodiment design and detail design, the establishment of the product architecture issue has not been tackled in depth in this study, as this task is nowadays a field of research on its own.

As the embodiment design and detail design phases are concerned with the development of solution principles for auxiliary function carriers, there is a clear similarity with the activities within the conceptual design phase. The differences are:

- the auxiliary function carriers are generally of less complexity and thus generally easier to design,
- the degree of novelty: many auxiliary function carriers are present in every product (in support or protection functions); designing these function carriers is then either a routine task or a plagiarism task,
- the embodiment design and detail design tasks are more well defined: the inputs and outputs of the corresponding function are now fixed, while this was not the case during the development of the main function carrier.

It is also possible that some of the results of this study are applicable for some conceptual design tasks.

In short, the terms *conceptual design phase* and *embodiment design and detail design phases* are used as follows in this document:

CONCEPTUAL DESIGN PHASE: Phase of clarification of the design task and of development of a concept in which at least the overall solution principle of the product-to-be is established.

EMBODIMENT DESIGN AND DETAIL DESIGN PHASES: Phases of transformation of the concept into a TS ready to be produced.

### 3.2.2 Embodiment and detail design process models

As mentioned in the introduction, the embodiment design and detail design phases have received little attention in comparison with the conceptual design phase. This problem was recognized already by Pahl (1983) and was the object of a workshop in the ICED conference in 1985. In 1990, Pahl recalled this issue and announced that a systematic embodiment design process model was under development (Pahl 1990). These efforts resulted in 2004 in VDI Guideline 2223 “Systematic Embodiment Design of Technical Products”. Apart from this guideline, few works are known: the most complete are those of Pahl & Beitz (1996), Hubka (1996) and Olsson (1995) ones, which are virtually unchanged since their first versions in the early 70s.

As VDI Guideline 2223 was not available when starting this study, the model by Pahl & Beitz (1996) was used as a starting point and is described in the next section. This is followed by the presentation of VDI Guideline 2223.

### 3.2.3 Pahl & Beitz’s (1996) model

Pahl & Beitz’s (1996) embodiment design process model is presented in Figure 3.6. Figure 3.7 presents the detail design process model.

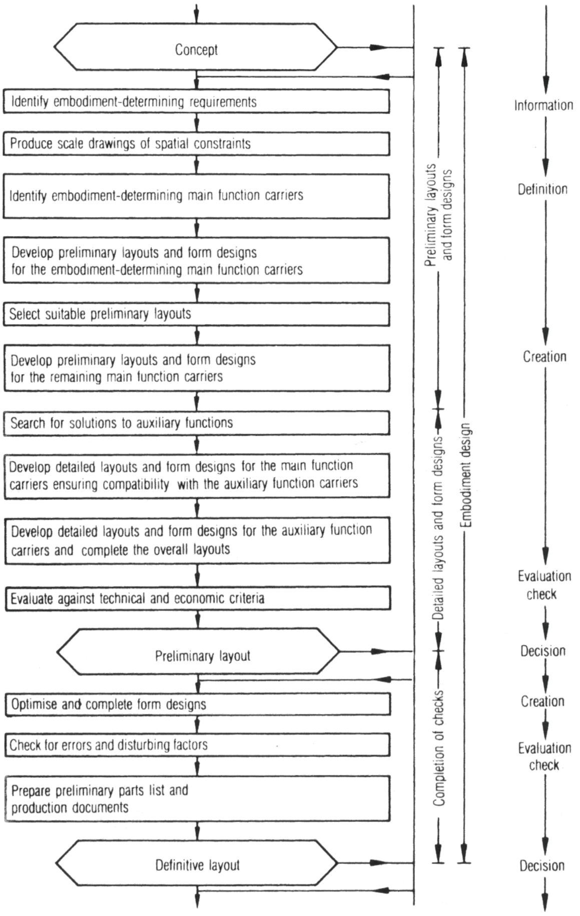

Figure 3.6 Steps of embodiment design (Pahl & Beitz 1996, p. 201)

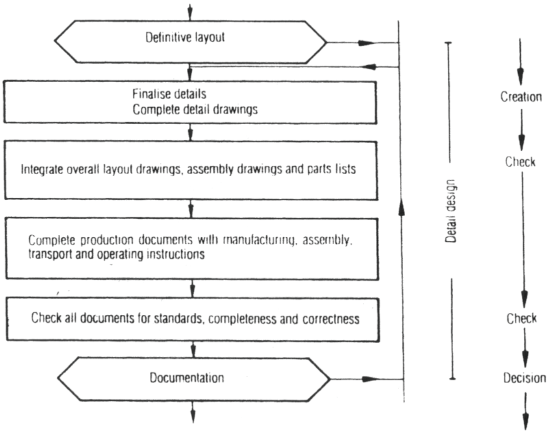

Figure 3.7 Steps of detail design (Pahl & Beitz 1996, p. 402)

The steps described by Pahl & Beitz (1996) are based on a progressive refinement of the properties of the TS and follow a PSP model close to the generic one presented in Section 3.1.4. The sequence proposed is highly general and merely helps the designer in planning his/her work. The heuristic proposed here is close to an intuitive, almost obvious one: in order to embody a TS the designer needs to know the spatial constraints; then he/she has to deal with the parts that will determine the structure of the TS, before dealing with the remaining parts. Finally, the designer will check for errors and finalize the documentation. The designer will find little help in the process model itself. Pahl & Beitz (1996, p. 200) assert that "it is not always possible to draw up a strict plan for the embodiment design phase" and therefore only present a general approach. Moreover, "in the embodiment design phase, unlike the conceptual phase, it is not necessary to lay down special methods for every individual step." (*Ibid.*, p. 203) The (creative) methods of solution search for conceptual design can be used here as well for the auxiliary functions (or use of design catalogues).

Otherwise, the designer is provided with *basic rules*, *principles*, *guidelines* and a *checklist* that are to be adapted to each situation. The *checklist* (Pahl & Beitz 1996, p. 206) is a list of generic factors one needs to take into account while designing (function of the TS, working principle, safety, ergonomics, production, transport, etc.). The *basic rules* are *simplicity* (e.g. few components, simple shapes), *clarity* (facilitates the prediction of the TS behavior) and *safety*. By observing them, "designers can increase their chances of success because they focus attention on, and help to combine, functional efficiency, economy and safety." (*Ibid.*, p. 207) Like the *basic* rules, the *principles* are general, but they have to be applied according to the type of problem. They are kinds of heuristics that have been derived both from practices and results from material sciences, mechanics and machine elements. These principles are:

- principle of force transmission (e.g. try to avoid sudden changes in the cross section),
- principle of the division of tasks (e.g. try to allocate one part to one function),
- principle of self-help,
- principle of stability and bi-stability,
- principle of fault-free design (try to eliminate potential faults).

Figure 3.8 shows an example of application of the principle of self-help. The pressure p on the cover of the tank increases the sealing effect (O) of the initial tension-screw force (I) in the layout shown on the right (Pahl & Beitz 1996, pp. 257-258).

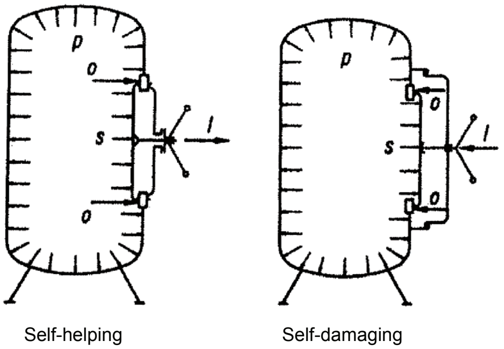

Figure 3.8 Layout of a tank cover (Pahl & Beitz 1996, p. 258)

The *guidelines* are procedures to more specific purposes: they cover the area of design for X.

The methodology presented by Pahl & Beitz (1996) is difficult to apply in concrete cases. Moreover, the product architecture is not emphasized in the process. This might be due to the fact that the form design of a part can change the architecture; nevertheless, the architecture often needs to be determined prior to the form design activities. There is also no clear differentiation between embodiment and form design. There is no defined procedure for applying the *basic rules* and *principles*. TS that respect the rules of *simplicity*, *clarity* and *safety*, and are in accordance with the *principles* are likely to be of better quality and cheaper than others, but this is an *a posteriori* analysis. These *basic rules* and *principles* are also taught by analysis of existing TS. The *basic rules*, *principles* and *guidelines* are not integrated into Pahl & Beitz's (1996) design process model, although one can guess that most of them are used mainly during the steps of creation and evaluation/check of the design.

### 3.2.4 VDI Guideline 2223

The guideline describes the embodiment process defined in VDI Guideline 2221 (1987) presented in Section 3.2.1. This corresponds to stages 4 to 6 of the general design process model of VDI Guideline 2221[9]. The guidelines responds to some of the criticisms directed towards Pahl & Beitz's (1996) model.

The guideline clearly differentiates form design from embodiment design, contrary to Pahl & Beitz (1996): "FORM DESIGN: Activity during which the designer establishes form and material properties of the form design elements[10]. EMBODIMENT DESIGN: Comprises the form design and the planning, control and monitoring of the form design process[11]." (VDI Guideline 2223 2004, p. 5) The guideline is thus articulated towards the form design (process, activities and use of rules and principles) and is

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[9] The conceptual design process model recommended by VDI is presented in VDI Guideline 2222 Part 1: "Design Methodology - Conceptualizing Technical Products" (1977).

[10] The term FORM DESIGN ELEMENTS is "the collective term for areas [surfaces] of components parts, form elements, component parts and combination of parts" (VDI 2223 2004, p. 9).

[11] The use in this thesis of the term *embodiment design and detail design phases* as the "phases of transformation of the concept into a TS ready to be produced" (see p. 29) is not inconsistent with this definition.

completed by the other elements concerning the embodiment (management of the embodiment design process, multidisciplinary work, CAD). The form design process model is presented in Figure 3.9. This design process model gives a greater importance to the product architecture than Pahl & Beitz's (1996) (phase 4).

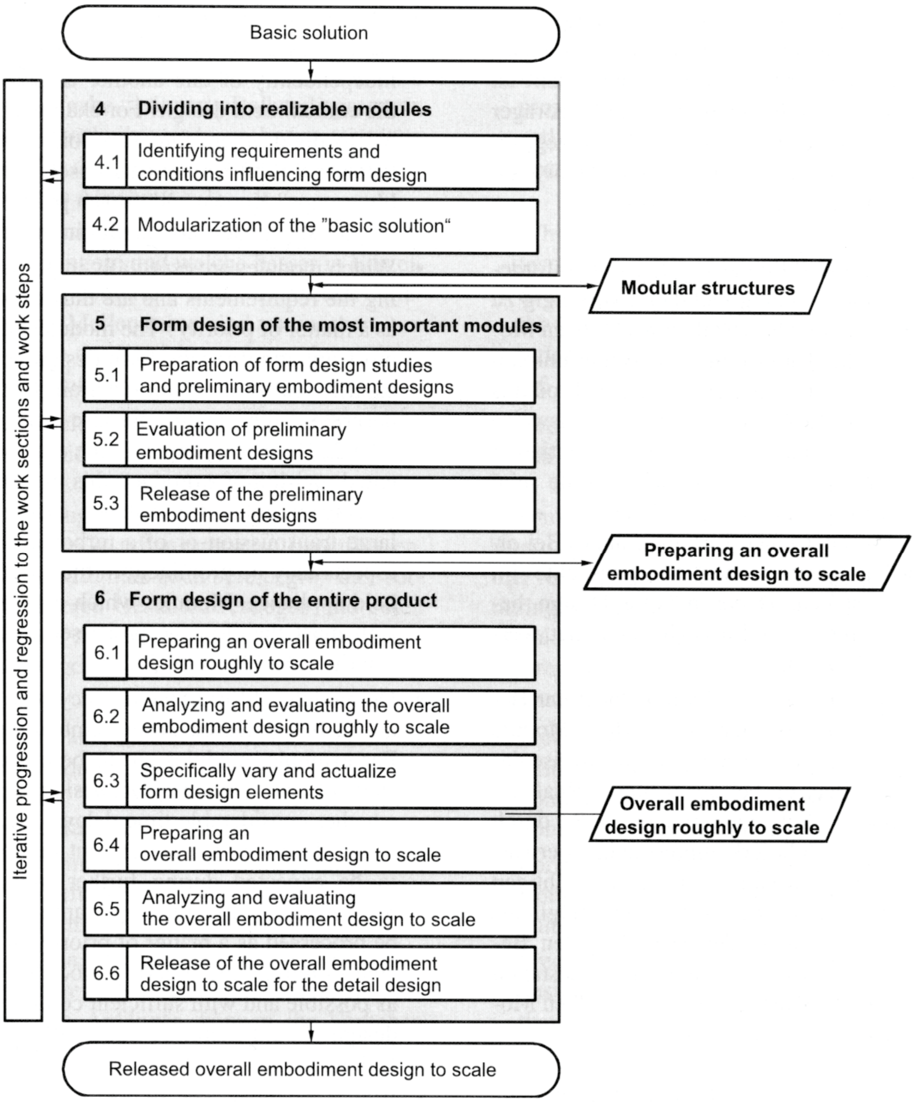

Figure 3.9 Form design process model (VDI Guideline 2223 2004, p. 19)

The guideline has profitably drawn inferences from the multidisciplinary work between design researchers and psychologists launched in 1985 in Germany (see Pahl et al. 1999b and Section 3.3). First, the design process model is far from normative. It is clearly stated that process model, presented as "strategic", must be used as an overall plan of action. During the design activity itself (at the "operational" level), the designer must act in accordance with the situation, which can lead to jumping some steps of the "strategic" form design process, for example. Second, the designer and his/her skills, experience and limitations are taken into account: a whole section of the guideline insists on the limit of the scope of the design process model and explains clearly its use in concrete cases.

A set of methods and tools for form design and the procedures to carry them out are also presented: analysis, variation, calculation, experimentation, evaluation and decision making (VDI Guideline 2223 2004, pp. 44-64). Variation is a method directly related to synthesis. It consists in the systematic variation of form features. Figure 3.10 presents possible variations of macro-geometric features. The micro-geometric features (surface finish, tolerances) can also be varied. The method is not new; it was developed in Koller (1976, pp. 74 ff) and is present in the literature in several variants (Ehrlenspiel 1995). This method is still what Schregenberger (1985) would call a "weak heuristic": it does not guarantee that the designer will obtain a working solution, while for example design catalogues do (see Section 3.2.5).

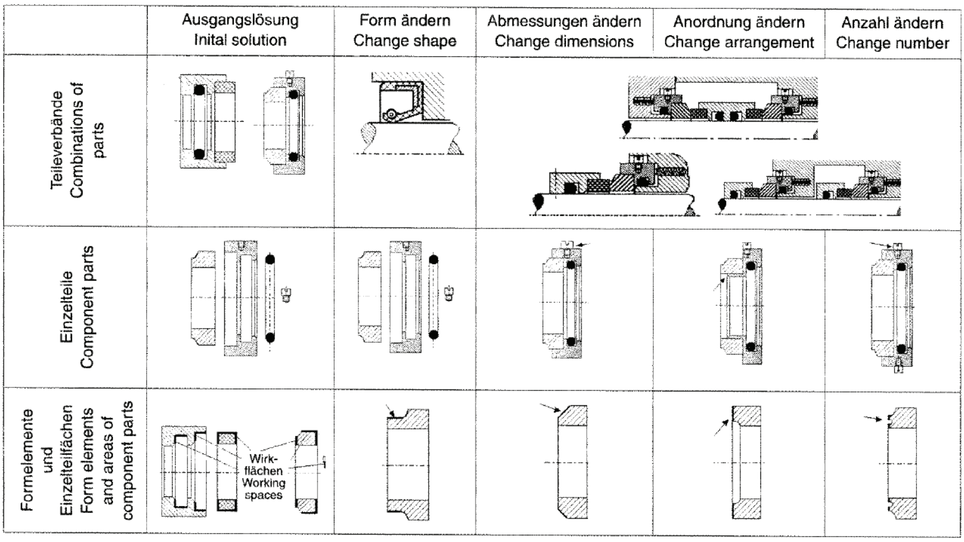

Figure 3.10 Variation of macro-geometric features (VDI Guideline 2223 2004, p. 51)

Finally, the guideline presents and extends Pahl & Beitz (1996)'s *basic rules*, *principles* and *guidelines*. They are no more central to the embodiment design process. Instead they are presented as *recommendations* for the designer, "which have proved successful in a large number of form design tasks and are of interest for a large number of users." (VDI Guideline 2223 2004, p. 64) The *basic rules* are the same as Pahl & Beitz (1996)'s: *simple*, *unambiguous* (instead of *clear*) and *safe*. *Principles* are defined as "strategies which lead to an appropriate form under certain preconditions" (*Ibid.*, p. 65). *Guidelines* are called *design rules*. To the rules has been added the notion of *form patterns*, which are regrouped as *types* and *styles of construction*. A TS always belongs to a certain type defined by its characteristics (e.g. lightweight, modular, mass-produced) "that indicate directly or indirectly form and material properties" (p. 67). *Styles of construction* are "typical basic forms of products which have been defined for specific sectors or applications" (*Ibid.*, p. 68), for example housings. These *patterns*[12] help the designer in choosing and reducing the variety of forms and materials available.

While Pahl & Beitz (1996)'s methodology focused mainly on the question "what to do", this guideline gives some concrete methods (e.g. variation), clarifying the use of the process model and of the *form design recommendations*, providing a beginning of answer to "how to do it?". This clarifies as well the research question of this thesis: The synthesis activities studied at levels 2 and 3 of the four-level design model primarily concern form design.

This guideline is a big step towards providing better help for the designer during the embodiment design phase, being apparently more accessible and easier to apply. This guideline will clearly play an important role in the following of the *overall* research project (contribution to the development of an embodiment design and detail design methodology). This is discussed Section 6.1.

### 3.2.5 Supporting tools

The designer primarily uses a pen, paper and a calculation instrument during synthesis; these were the only tools the participants had at their disposal during the experiments (together with access to all the documentation they wanted). Concerning the synthesis activities in the embodiment design and detail design phases, two tools are actually available that aim specifically at giving form to the TS: topology optimization and design catalogues. These support tools were not used during the experiments, primarily because they would have prevented the observation of a "genuine" activity of synthesis. The other countless tools that are employed during design are more for analysis of the TS generated.

With topology optimization it is theoretically possible, given a set of forces and moments, to compute a stiff structure that needs as little material as possible. The form obtained could be used as a starting point or inspiration source for form design[13]. As shown by the example presented in Figure 3.11, there is then a need to adapt the optimal solution for manufacture.

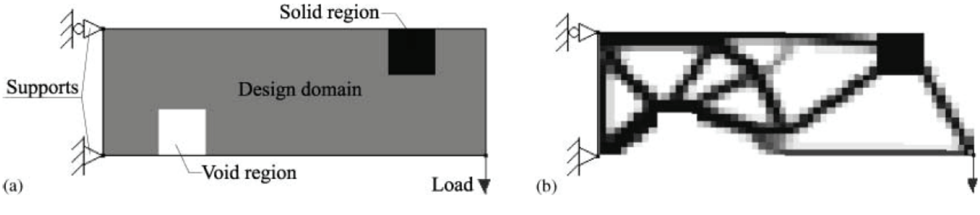

Figure 3.11 (a) A typical topology optimization problem: a design domain with passive areas (white is fixed to be void and black is filled by a material), supports and a load.
(b) An optimal design for the described problem (Tcherniak & Sigmund 2001, p. 181)

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[12] *Patterns* could have been translated to *models* as the original German word is *Vorbild*.

[13] Prof. Pierre Duysinx, Lucid Group, University of Liège, personal communication.

The concept of design catalogue has been especially developed in Germany. A guideline for the development and use of design catalogues has even been released ("VDI Guideline 2222 Part 2: "Design methodology - generating and using design catalogues" 1982). A general description of design catalogues can be found in Pahl & Beitz (1996, pp. 89-84), and is partially reproduced hereafter[14]. Design catalogues are collections of known and proven design solutions. They contain data of various types and solutions on distinct levels of embodiment. Thus they may cover physical effects, working principles, principle solutions, machine elements, standard parts, materials, off-the-shelf components, etc. Design catalogues are based on the same principle as the manufacturers' component catalogues: a set of solutions for a design problem category defined by a set of characteristics. The characteristics help the designer in the preliminary selection and evaluation of a solution and, in the case of computer-based catalogues, they can also be used in the final selection and evaluation. Examples of computer-based catalogues are described in Franke et al. (2004) and Tumkor (2000). Some catalogues can be used for synthesis in the later phases of the design process: they give the best form features possible for given characteristics of particular embodiment design problems. Figure 3.12 shows an extract of a catalogue for shaft-hub connections based on Roth (1982). The solutions are concrete enough, thanks to the specification of the form design features, for the embodiment design phase to start with a scale layout drawing.

## 3.3 Questioning the normative design process models: the designer in the center of the design activity

### *3.3.1 Reflections on normative design process models*

The earliest criticisms concerning the design process models of the methodologies presented above involved their normative aspects. Ever since the first ICED conferences, many researchers have considered that these design process models, of German background, are far too procedural and do not allow the designer any freedom. These process models aim at being as general as possible for all kinds of products and product developments (VDI Guideline 2221 (1987) also addresses the design of all artifacts from mechanical products to production plants and software), but they are difficult to adapt to each particular case.

The other criticism is the validity of the process models themselves and the hypotheses they are built on: It questions whether a design methodology based on the concepts of function and working principle is an optimal or ideal one. According to Pahl et al. (1999b), few empirical investigations confirmed their efficiency.

Beyond these aspects, Franke (1985) identified another major problem: as the design process was laid down, it was not adapted to the concrete design activity. Franke simply asserts that it is virtually impossible to describe a product in term of function if some idea of the concrete product is not present. Moreover, once a function is determined, the concrete embodiment determines the auxiliary function: "Only from

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[14] The quotation signs have been omitted for the sake of readability.

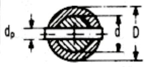
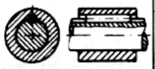
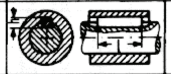
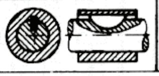
| Classifying criteria | | Solutions | | | | Solution characteristics | | | | | | | | | | | | | | | | Remarks | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type of interface | Type of force transmission | Equation | Name | Configuration | | Transferable torque | Torque transmission depending on | | Axial forces | Stress concentration | Applicable for | Behaviour at overload | Centering possible | Unbalanced force | Axial displacement of hub | Hub moveable | Joint adjustable | Shaft diameter (mm) | Material | Manufacturing effort | Assembly effort | Standard (DIN) | Application examples | Remarks |
| 1 | 2 | 1 | 2 | 3 | No. | 1 | 2 | | 3 | | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| Normal (form fit) | Direct | $T \le K \cdot \frac{d}{2} \cdot A_s \cdot \tau_{max}$<br>or<br>$T \le K \cdot \frac{d}{2} \cdot A_p \cdot \sigma_{max}$ | spline shaft |  | 1 | large | h.<br>i.<br>l | shaft diameter, (form) factor, centering factor, material | – | large | pulsating or alternating load | fracture | yes | no | clearance fit | yes | no | 10-150 | shaft:<br>37 Cr 4<br>41 Cr 4<br>42 CrMo4 | high | small | 5461/63<br>5471/72 | toothed wheels | exterior, flank, interior centering possible |
| | | | involute spline shaft |  | 2 | | | | – | | | | | | | | | | | | | 5480<br>5482 | | short hub possible |
| | | | serrated shaft |  | 3 | | | | – | medium | | | | | | | | 150-500 | | | | 5481 | | |
| | | | 3-polygon-shaft |  | 4 | | e.<br>i.<br>l | | – | | pulsating or alternating load | | self-centering | no | clearance fit without load | | yes for taper | 10-100 | | small, special machinery necessary | | — | | used for short and thin hubs, conical shaft end possible, broaching or grinding necessary |
| | | | 4-polygon-shaft |  | 5 | | | | – | | | | | | | | | 10-100 | | | | — | | |
| | Indirect | | transverse pin |  | 6 | small | $\frac{d_p}{D}$ | | are supported | large | — | | yes | yes | — | | yes for taper pin | 0.5-50 | pin:<br>4D, 5S,<br>6S, 8G,<br>9S, 20K<br>St 50K<br>St 70<br>St 60 | medium | medium | 1.7<br>1470-77<br>1481,<br>6324,<br>7346 | power stretcher, machine tools, vehicles | taper and grooved pin possible |
| | | | tangential pin |  | 7 | | | | | | — | | | | — | no | | | | | | | | |
| | | | in line pin |  | 8 | | $\frac{d_p}{l}$ | | – | medium | — | | | | clearance fit | | | | | | small | | | |
| | | | key joint |  | 9 | | h.<br>l<br>b | | – | large | — | | | | | | no | 5-500 | spring<br>St 60<br>shaft,hub:<br>GG, GS<br>St | | | 6885 | | |
| | | | Woodruff key |  | 10 | | | | – | | — | | | | | | | | | | | 6888 | | |

Figure 3.13 Extract of a catalogue for shaft-hub connections (Pahl & Beitz 1996, p. 96; after Roth 1982)

the selection of a material combination will the expansion problems be known, and only after the selection of the joints ("Trennfugen" in German) that are dependent of the assembly and means of production will the leakage problem be known" (Franke 1985, p. 919, in translation by the author). That means, in other words, that a reliable solution principle evaluation and selection presupposes a good knowledge of its embodiment and details, and that shifts between conceptual design, embodiment design and detail design are necessary. This problem is nowhere reflected in the existing design methodologies.

An extensive review of the difficulties of normative design process models to match concrete design situations can be found in Bender (2004, pp. 39-47). In light of these arguments, one part of research in engineering design is now focusing more on the concrete design activity, instead of focusing solely on the development of ideal process models. Such a research programme implies observations of the design activities and all the factors that influence them. This put the designer in the center of the research study: What does a designer do, what can he/she do, what can't he/she do, where is the need for help and improvement? The cognitive and social aspects of the act of designing need to be charted.

This view is the one adopted for the *overall* research project. The "real" embodiment design and detail design process has to be studied; the "characteristics" of the designer have to be determined prior to the development of any methodology. As this thesis presents the results of the study of levels 2 and 3 of the design process, the social aspects have not been reported. The next section presents a literature review of the cognitive aspects of the engineering design activity.

As mentioned earlier, if the methodologies themselves are questioned, the concept of methodology must not be discarded: a normative process model is needed for planning the design activity, managing it and controlling it. Such a process is easy to integrate and adapt in the whole product development process of a company. For the teaching of design, it is also a simple way of understanding the different moments of the design activity. In their article "A rational process: how and why to fake it", Parnas & Clements (1986) add that designers need guidance, even at the activity level, and a design process model helps them to get started and persevere if problems arise; the project report needs to be structured and edited in a way that is understood by outsiders — it helps to have a common view of the overall process; the different elements created during the project can be re-used for another design project if they are presented in a standardized way. Pahl (2005) emphasizes all these arguments and advises the reader on how to use and adapt the different VDI Guidelines 2221 (1987), 2222 (1977) and 2223 (2004), as well as Pahl & Beitz (1996)'s model, to achieve concrete situations. Finally, the last VDI Guideline to date, VDI Guideline 2223 (2004) pays particular attention to the design process at a strategic level, the design activity at an operational level, and the designers skills and "limitations".

### 3.3.2 The cognitive aspects of the engineering design activity

This aspect has been covered in the appended Paper A. A summary of this review is to be found in Section 4.1, along with the summaries of the other appended papers.

In Sections 3.3.2.1 and 3.3.2.2 this literature review is revised with regards to new references that are related to the study presented in this document. In Section 3.3.2.1, the elements concerning the cognitive aspects of design are added. The results from studies on the embodiment design or detail design that the author was unaware of during the development of the literature review are presented in Section 3.3.2.2.

#### 3.3.2.1 Complementary cognitive aspects of design

In his book *Integrated Product Development*, Ehrlenspiel (1995) dedicates a whole section to problem solving in design and how the individual designer influences the design quality (whether the design result is good or not). Ehrlenspiel's aim, like the one adopted here, is to integrate or at least to take into account these influences in a methodology. With the help of the following descriptive studies: Dylla (1990), Dörner (1989), Fricke & Pahl (1991), Hoover et al. (1991), Stauffer & Ullman (1988), and a warning that none of these results were statistically validated, Ehrlenspiel presents the archetype of a "successful" designer (Ehrlenspiel 1995, p. 108):

- The successful designer spends more time with the analysis and formulation of the product requirements;
- his/her solution space is larger;
- he/she prioritizes the tasks of his/her work;
- he/she generates more variants;
- he/she analyzes the generated solutions more accurately and thus spends less time at this activity;
- he/she has a good spatial representation skill;
- he/she has a good control of the process. More emotional and superficial designers are less good than the former ones.

This archetype confirms and reinforces the righteousness of the prescriptive models concerned. Ehrlenspiel warns, however, that the individual differences among designers play a huge role: the designer who developed the best artifact among Dylla (1990)'s six participants in his experiments could not be described by this archetype.

Bender (2004) reviews the works of 27 authors covering some 35 field or experimental studies. Among Bender's findings, the following completes the literature survey of Paper A:

- Some studies link the creative skill of the designer to the multimodal model of memory: knowledge is stored in different representation modes. The pictorial and conceptual representation modes are those most evoked in design research. Switching between these representations while performing a design activity yields better results.

- The design process is more corrective than generative (see next section).
- Individual characteristics have significant influences on design quality.

These individual characteristics are detailed in Günther (1998). Günther (cited by Bender 2004, p. 95)considered the following characteristics: experience in design, heuristic competence, adequate problem-solving behavior (problem analysis, solution generation, evaluation), emotionally loaded, regression (tendency to flee from the problem), resignation, spatial representation skill, motivation. 18 designers had to solve a design assignment under in an experimental setup. The design quality was significantly positively correlated to the design experience, and significantly negatively correlated to an emotional and regressive behavior. It is noticed that there was no correlation between a good spatial representation skill and design quality, in contradiction with the results Ehrlenspiel (1995) presented.

### 3.3.2.2 Studies of the embodiment design and detail design phases

In Paper A, only two studies that dealt with the embodiment design and detail design phases were reported: Fricke (1999) and Römer et al. (2000). The former focused on the task clarification phase of the whole design process and the second on the problem analysis step of the design process viewed as a problem-solving process, that is, not specifically on design.

Bender (2004) mentions the earlier German study of Dylla (1990). Dylla studied the whole design process by means of an experimental setup identical to ours: six designers were videotaped and asked to think aloud. Their design process was then analyzed by means of verbal protocol analysis. Concerning the embodiment design phase, Dylla observed that most of the time the designer used a corrective procedure to develop solutions, rather than a generative one. A generative procedure is the generation of one solution, then development of variants and selection of the best one (see Figure 3.14).

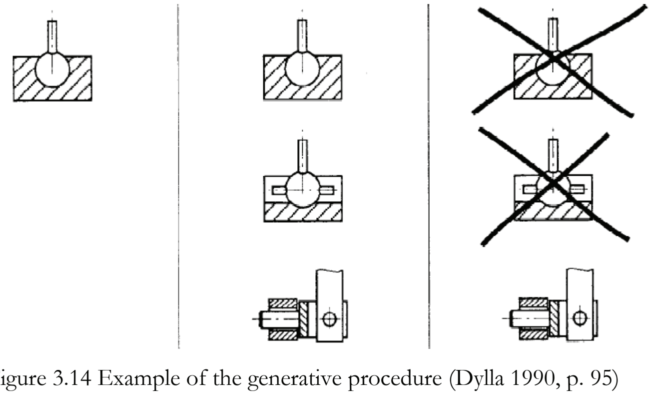


Figure 3.14 Example of the generative procedure (Dylla 1990, p. 95)

The corrective procedure is the development one solution and the subsequent correction at a more concrete level, without generation of variants (see Figure 3.15). On average, the designers used the corrective procedure in 81% of the solution developments episodes.

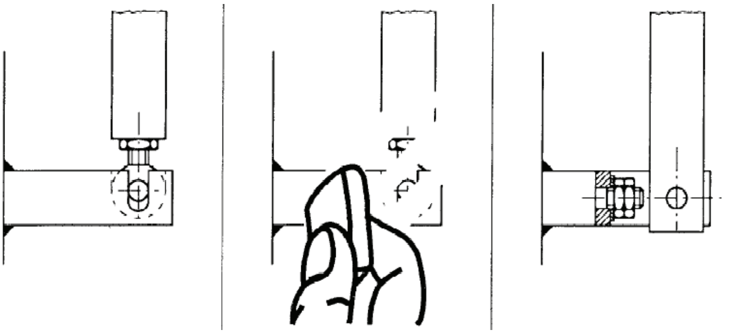


Figure 3.15 Example of the generative procedure (Dylla 1990, p. 96)

Günther & Ehrlenspiel (1999) compared designers from practice[15] and designers with systematic design education. 18 experiments were performed, with the same experimental setup and design task as Dylla's (1990). Günther & Ehrlenspiel split the embodiment design and detail design phases into rough embodiment design and final embodiment phases. The signification and the content of the two phases was not specified in the paper, but the first phase should correspond roughly to stages 4 and 5 of the design process model of VDI Guideline 2221 (1987) and the second to phases 6 and 7 (see Figure 3.5, p. 28). They noticed that the designers from practice revealed different behavior than the designers with systematic education. They either passed over the rough embodiment phase or developed a rough embodiment of the artifact with many changes between the conceptual design phase and rough embodiment design phase, prior to a non-interrupted phase of final embodiment design. The designer with systematic design education tried to follow the learnt design process model. Günther & Ehrlenspiel label practicing designer's procedure as *sub-problem-oriented*, and the designers with systematic design education's procedure as *phase-oriented* (see Figure 3.16). Günther & Ehrlenspiel (1999) draw up a list of advantages and disadvantages of the *sub-problem-oriented* procedure, but do not draw conclusions regarding the impact of this procedure on the design quality. They advise, however, not teaching the systematic approach to design to the designers from practice. They propose instead a procedure that adopts their approach but supplements it in order to overcome the observed flaws (e.g. need to document their work, to spend more time on list of requirements).

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[15] experienced designers from practice who have neither education at a university nor education in design methodology (Günther & Ehrlenspiel 1999, p. 439).

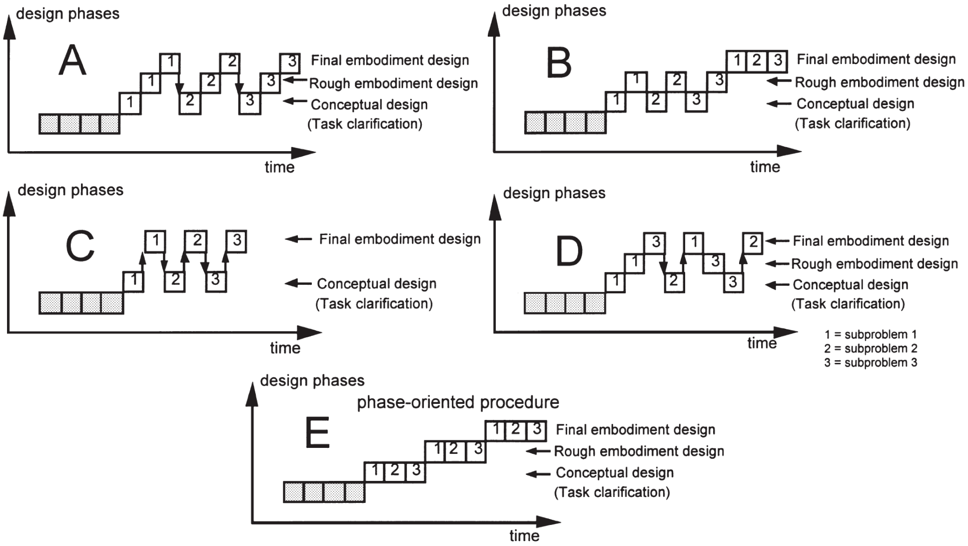

Figure 3.16 Figures A, B, C and D are alternatives of the sub-problem-oriented procedure. E shows the phase-oriented procedure for comparison (Günther & Ehrlenspiel 1999, p. 445)

Finally, Bender (2004) studied the conceptual design and early embodiment design phases. The early embodiment design phase corresponds to the rough embodiment design phase of Günther & Ehrlenspiel (1999). The results concerning the early embodiment design phase are also reported in Bender & Blessing (2004). Bender considered that there are four types of design process approaches:

- Hierarchically phase-oriented: The design activity follows a phase-oriented process model like VDI Guideline 2221 (1987) and all the subsystem of the product are developed at the same level of refinement before beginning the next phase (corresponds to Günther & Ehrlenspiel (1999) Figure 3.16.E).
- Hierarchically object-oriented: One subsystem is completely developed following a phase-oriented process before another subsystems is developed (corresponds to Figure 3.16.A).
- Opportunistic and associative: This is a mixture of a hierarchical decomposition with an opportunistic, local and bottom-up proceeding (could correspond to Figure 3.16.B, Figure 3.16.C or any other combinations).
- Trial and error (corresponds to Figure 3.16.D).

Their conclusion is that the design quality is best when the opportunistic and associative approach is employed. This implies that a phase-oriented process, when strictly applied, does not lead to a better design quality. Notice that Bender & Blessing (2004)'s three last types of design approach correspond to the *sub-problem-oriented* procedure in Günther & Ehrlenspiel (1999)'s classification. Günther & Ehrlenspiel (1999)'s classification at this point seems too general and fails to account for the specificities of the possible alternatives of *sub-problem-oriented* procedure.

# 4 Summaries of the appended papers

*This chapter gives a summary of the findings published in the appended papers. Paper A is a literature review on the cognitive aspects of the engineering design activity. Papers B, C and D present the results of the study of synthesis during the embodiment design and detail design phases. Paper B presents a model of synthesis modeled as a PSP. Paper C presents the strategies and tactics of the designer under the activity of synthesis. Paper D presents a refined study of the students' synthesis activities and the implications for the teaching of the embodiment design and detail design process. These results are discussed Section 5.1.*

## 4.1 Paper A – The Cognitive Aspects of the Engineering Design Activity

This publication is a literature review on the current research on cognitive aspects of design. It presents the contribution of cognitive psychology to PSP and the current research on cognitive aspects of design: general scopes of the studies of this domain, the design phases concerned, the cognitive aspects studied, the study methods and the findings. The results are reproduced in Table 4.1. Notice that the studies do not all aim at contributing to the development of design process methodology.

This literature review is revised in Sections 3.3.2.1 and 3.3.2.2.

Table 4.1 Results of the survey on cognitive aspects of design

| | |
|---|---|
| ***General scopes of the studies*** | Design theory<br>Design process methodologies<br>Design process as a whole<br>Design supports<br>Design education<br>Theoretical implications for cognitive psychology |
| ***Objects of the studies*** | Clarification of the task<br>Conceptual design:<br>    Problem understanding<br>    Idea generation<br>    Evaluation<br>Design supports:<br>    Sketching<br>    CAD system<br>    AI systems<br>Designer's characteristics |
| ***Study Methods*** | Experiments:<br>    Verbal protocol analysis and Sketch analysis<br>    Quantitative study |

Table 4.1 Results of the survey on cognitive aspects of design (continued)

| | |
|---|---|
| ***Cognitive approaches*** | Problem solving:<br>Problem space<br>Heuristics<br>Thinking process<br>Knowledge-based models:<br>Retrieval and use of information<br>Knowledge representation: concepts and categories, schema<br>Imagery<br>Memory<br>Human intelligence<br>Artificial intelligence |
| ***Findings for problem solving in the process of design*** | Confirmation of the validity of prescriptive methods<br>But<br>Claim for an acknowledgement of findings in cognitive psychology:<br>Dealing with early appearance and persistence of a core idea<br>Failure to search for alternative solution<br>Design fixation (inclination to stick with early satisficing solutions)<br>Superficial assessment, subjective judgment<br>Hypothesis of inhibitory memory processes subsequent to recognition of familiar solution<br>Lack of flexibility in designer's thinking behavior<br>Claim for design supports as extensions of the designer:<br>Sketching<br>Improving 3D system<br>Intelligent systems for retrieval and reuse |

## 4.2 Paper B – A Descriptive Model of the Design engineer's Problem Solving Activity During the Later Phases of the Design Process

This paper is based on the hypothesis, presented in Section 3.1.4, that the design process can be modeled as a PSP and that the PSP is sequential. A first study of the design process as a PSP had been carried out earlier (Motte et al. 2004). In this first publication, it was revealed that the existing coding schemes used for the conceptual design phase did not fit the observed episodes, as mentioned in Section 2.4.2.2.1. That implied that the PSP itself was slightly different from the one observed in the concept design phase. The coding scheme comported seven episode categories: information search; mechanical description/model of the solution; synthesis[16]; dimensioning; evaluation; drawing; organization. Synthesis was composed mainly of an interplay between generative episodes and mechanical modeling of the technical system. The mechanical modeling episode was used both for analysis, verification and as an input to another generative episode. A pattern of a general problem-solving strategy could be extracted: the designers quickly understood the problem, did not try to know more than the given assignment; developed no more than 2 alternatives; rapidly selected one of them and then studied and developed this alternative in detail (by dimensioning or not — two students did not dimension, two experts dimensioned with only the help of their experience).

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[16] For lack of a better expression, the generative episodes are called "synthesis", the same denomination as the design activity studied.

In this paper the description of the designer's PSP is deepened. The coding scheme was extended mainly by using the recursivity property of the PSP: the first four categories were divided in sub-categories following the generic PSP pattern: intelligence, design, evaluation. Moreover the evaluation episodes were studied more deeply (see Tables 1 and 2 in Paper B). The result of this study was the refined descriptive problem-solving activity model reproduced in Figure 4.1.

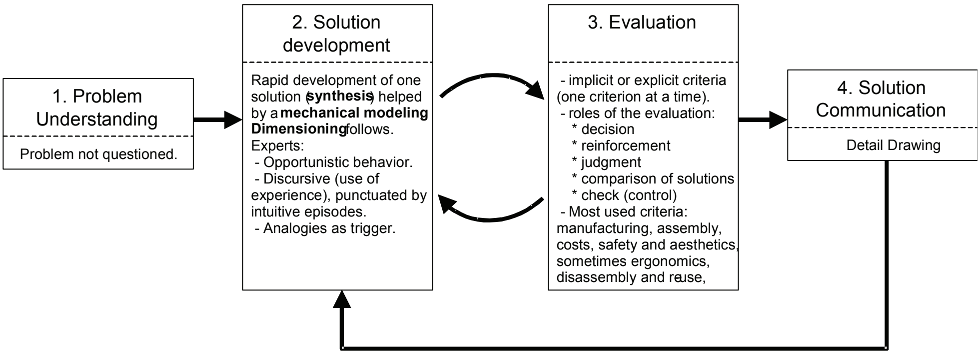

Figure 4.1 Descriptive problem-solving activity model

The solution development step was also refined: The designer rapidly develops one solution proposal (synthesis) helped by a mechanical modeling of this proposal, after which dimensioning follows. Interactions between the mechanical modeling activity and the dimensioning activity have seldom been observed (which is counter-intuitive). This process of actions is represented in Figure 4.2. The sequence of transitions between the actions that has been most often observed follows the order i-iv.

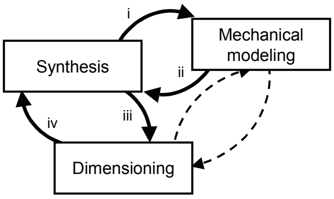

Figure 4.2 The sequencing of activities during solution development

Concerning the evaluation moments, the designer constantly checked the accuracy of his/her work, using implicit or explicit criteria (generally only one), but did not try to evaluate it in a more rigorous way at the end of the assignment.

Some events were also observed that had an impact on the design process and the results: when material, components and joints were chosen from the beginning, the design process went more rapidly. The sub-problems were generally treated separately and deeply by the experts. The behavior of the expert during synthesis was discursive (use of experience), punctuated by intuitive episodes. Designers sometimes used analogies as triggers. The students used a case-driven analogy (by referring to a known, similar, case), while the experts used more abstract comparisons, triggering solution ideas (schemata-driven analogy). All designers faced problems with proportions and measures, which were not taken into account during the solution development and caused them to come back to synthesis.

## 4.3 Paper C – A Study of the Mechanical Design Engineer's Strategies and Tactics during the Later Phases of the Engineering Design Process

While the modeling of the PSP is relatively general, the strategies and tactics must be peculiar to the performed task. The coding scheme consisted of design tasks that were considered basic in the embodiment design and detail design phases. They were derived from the literature (Hubka & Eder 1996; Pahl & Beitz 1996) and by observation of the designers. They are reproduced in Table 4.2.

Table 4.2 Basic design tasks

| ***Abbr.*** | ***Design Task*** | ***Shortened definition (see also Paper C)*** |
|---|---|---|
| Id | **Identification of the problem** | |
| | **Layout and form design** | |
| $L_{ss}$ | Scale of spatial constraints | Define (calculate if necessary) the space needed for the technical system. |
| $L_{sd}$ | Synthesis | Design (embodiment) at an abstract level of the technical system. |
| $L_{cc}$ | Choice of components | Dimensioning and choice of the components (standards or not). |
| $L_{cm}$ | Choice of material | Choice of the material (steel…). |
| $L_{cj}$ | Choice of joints | Choice and dimensioning of the fixation systems that assemble the components together or with the environment (weld, screw). |
| $L_{compa}$ | Ensure compatibility/interface | Consideration of the compatibility of the different parts. |
| | **Evaluate against technical and economical criteria** | |
| $Ev_c$ | Find criteria | Criteria used to evaluate the design. |
| $Ev_{of}$ | Find objective function | Modeling of the task into a function to optimize. |
| $Ev_t$ | Evaluate against tech. criteria | |
| $Ev_e$ | Evaluate against econ. criteria | |
| | **Check** | |
| $Ch_e$ | Check for errors | Verification of any possible error in the design or the drawing. |
| $Ch_f$ | Check for disturbing factors | Check for possible factors that could influence the usual use of the TS. |
| D | **Detail drawings and documentation** | |

Moreover, whether the designer used the *basic rules*, *guidelines* and *principles* and *factors* (Pahl & Beitz 1996) was checked. An example of the design process of one of the experts along the basic design tasks, *basic rules*, *guidelines* and *principles* and *factors* is reproduced in Figure 4.3.

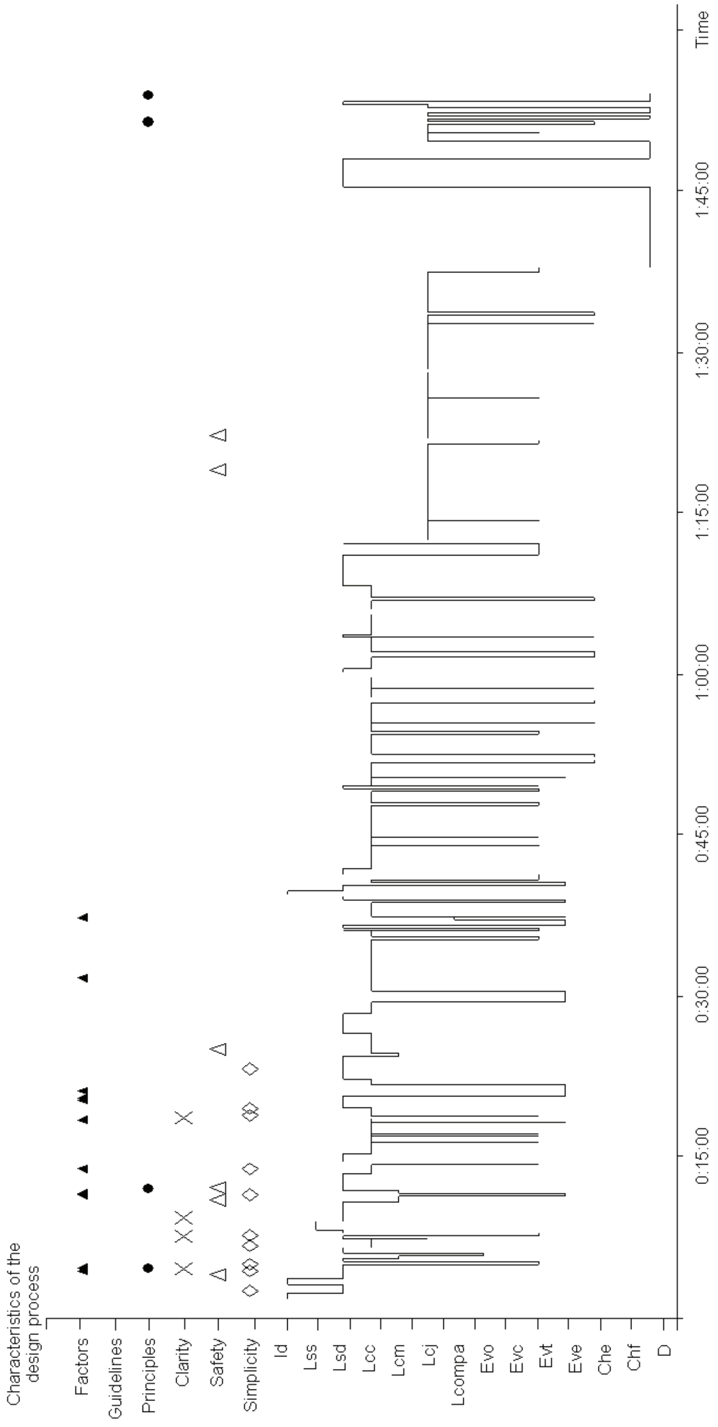

Figure 4.3 The design process of an expert

From the analysis and comparison of the design process of the six designers, the general strategies followed by the experts and the students could be extracted. At the same time, from the events that slowed down the design process or resulted in errors, a list of "weaknesses" was established. Some redundant results with the PSP study (Paper B) could be observed, due to the fact that some categories of the coding schemes were similar. Notice for example in Figure 4.3 that the "detail drawing and documentation" (D) episode resulted in new "layout and form design" moments. The experts' general strategy and tactics as well as the "weaknesses" of both students and experts are presented in Table 4.3.

Table 4.3 Strategies, tactics and weaknesses

| ***Strategies*** | ***Tactics*** | ***Weaknesses*** |
|---|---|---|
| *Experts:*<br>General Strategy:<br>Rapid understanding of the problem.<br>Considering, very early in the process, the shape of the parts and their interactions.<br>Concrete selection of materials.<br>Optimized selection of standard components.<br>Dimensioning of the joints.<br>Variations:<br>Dimensioning by experience or by mechanical analysis.<br>Often depth-first strategy.<br>Clear method that is loosely followed. | *Experts:*<br>Think in terms of standard components.<br>Think in terms of concrete shapes.<br>Document the work.<br>Detail drawing.<br>Use of basic rules.<br>Criteria:<br>Minimize costs.<br>Avoid unique parts.<br>Take production into account.<br>Wait until late before using principles and guidelines. | Do not ask beyond the assignment.<br>Do not plan design activity (at an operational level).<br>Do not use a developed objective function.<br>Check activity considered as secondary.<br>Basic rules often followed only at the beginning of the design process.<br>No check for other factors than "costs" and "manufacturing/assembly". |

## 4.4 Paper D – Comparative Study of the Student's Design Process: Implications for the Teaching of the Later Phases of the Mechanical Engineering Design Process

In Papers B and C, the students' design process was mainly compared to the experts'; in Paper D, the junior's activities are compared to the seniors'. The seniors had already followed the course on embodiment design and detail design, had practiced their knowledge in an industrial project during their last year and were finishing their Master's theses, while the junior was about to attend the course. In this course, the students were taught joint dimensioning, *basic rules*, *guidelines* and *principles*, but no process model was presented. The reason why the focus is put on the students is that they are certainly the only designers who will learn a new (or improved) design methodology, even if this is primarily intended for the industry. Indeed, it is believed that if practitioners have a life-long learning of design methods and tools, fewer will actively try to change their practice. Thus the students are the first to directly benefit from the development of a new design methodology. It is important to know what students can and cannot perform, with or without any formal knowledge of the embodiment design and detail design process. The observations of these two categories of students permitted extracting the important hints to focus on for the future development of a design methodology for synthesis.

The study embraced both levels 2 and 3 of the four-level framework, that is, the design process as a PSP and the strategies and tactics (including the use of *basic rules*, *guidelines* and *principles* and *factors*) used by the students. The most important results are that the course suppresses the *adhocism* (Bender & Blessing 2004) observed on the part of the junior, but the teaching of a list of *basic rules*, *guidelines* and *principles* is not effective even after almost a year of practice. The impact on the design quality may be affected after an extended period of time, but one can wonder whether it is the acquired experience that is in fact responsible for the acquisition of such skills. Moreover, the seniors neglected several points that are taken into account by the experts: design interface problems, early concretizations, and systematic selection of standard components. The students had also a tendency not to document their work, which resulted in a loss of time. They did not question the problem sufficiently, and developed very few alternatives, although they had knowledge and experience of conceptual design methods (notice that the experts presented the same design activity pattern). Both the junior and the seniors took into account only a few factors (production/assembly, costs…). If the students rapidly assimilate the simplicity rule, the rules of safety and clarity need more time. This must be emphasized during the teaching of these rules. The results are summarized Table 4.4.

Table 4.4 Differences in strategies, tactics and design operations between juniors and seniors

| ***Strategies*** | ***Tactics*** | ***PSP*** |
|---|---|---|
| Seniors:<br>Follow roughly the same process as experts, but considered late in the process the shape of the parts and their interactions, which led to geometrical problems. Dimensioning by mechanical analysis. | Seniors:<br>Do not document the work.<br>Do not use detail drawing.<br>Postpone product concretization.<br>Do not avoid unique parts. | The PSP was similar between seniors and juniors, and similar to that of the experts' (Paper B):<br>Problem understanding:<br>Did not ask beyond the assignment.<br>Solution development:<br>Interplay between synthesis, mechanical modeling and dimensioning, in this exact order.<br>Evaluation operations:<br>- implicit or explicit criteria (one criterion at a time).<br>- roles of the evaluation: decision, reinforcement, judgment, check (control), comparison of solutions. |
| Juniors:<br>Do not follow any determined process. Do not prioritize any activity. Avoid dimensioning. | Juniors:<br>Do not set any criteria.<br>Adhocism ("I cannot solve this problem, so this is not my problem.") | |
| *Weaknesses:*<br>Do not plan design activity.<br>Do not use a developed objective function. | *Weaknesses:*<br>No check for other factors than "costs" and "manufacturing / assembly". (Students: seldom check their design.)<br>The students spent more time on the mechanical analysis due to lack of experience and poorer use of the simplicity and clarity rules. | *Weaknesses:*<br>Developed only one or two solutions.<br>Check activity considered as secondary.<br>Basic rules often followed only at the beginning of the design process. |

# 5 Conclusion

*In this chapter, the results are discussed in the light of the goal and hypotheses set up for this thesis as well as with reference to the complementary findings in the literature, especially VDI Guideline 2223 (2004). In addition to this discussion, some reflections on the research approach and on the experimental method are also included.*

## 5.1 Discussion of the results

The research question formulated for this thesis (see Section 1.2) was: **How does the designer perform synthesis in the later phases of the mechanical engineering design process?**, which was transposed into 1) Is there a design process pattern that the designer follows and, if yes, what is this design pattern? 2) What are the flaws in the design activities performed by the designer? The hypotheses (see Section 1.4) were 1) the ability and experience required in problem solving differ between embodiment/detail design and conceptual design, and 2) synthesis could be separated from analysis.

The two questions are answered in Papers B and C. A general design strategy was extracted from the observations and a series of weaknesses has been listed and presented Table 4.3 (p. 48) and Table 4.4 (p. 49).

The first hypothesis can be partially verified. As the protocol schemes used for conceptual design to describe the designer's PSP could not be applied for the analysis of the protocols, it seems that the ability and experience required in problem solving differs between embodiment/detail design and conceptual design. If the PSP differs between the different phases, this should imply that the ability and experience required are different, which justifies this study. However, this assertion needs to be taken with caution: only three different protocol schemes describing the conceptual design process as PSP were studied (Atman et al. 1999; Ball et al. 1998; Purcell & Gero 1998). Other coding schemes may be more effective. However, probably none would have helped to capture the interplay between synthesis, mechanical modeling and dimensioning. To completely verify this hypothesis, it should be necessary to check if the PSP model developed to describe the embodiment design and detail design would not work when applied to the conceptual design process.

The validity of the second hypothesis can be questioned. The experts could almost fully dimension the technical system and would have used analysis tools to analyze the design after synthesis, which tends to confirm the hypothesis. But the students disclosed (during the experiment or during the post-experimental interview) that they would have performed a finite element analysis (FEA) very early in the design process and elaborated on the results. It is also probable that the "natural" design process of the students was only partially captured. What is the impact of this bias on the results of this study? To answer this question, the descriptive model of the design process presented here would need to be compared to a similar experiment where the student has access to analysis tools. However, these results still indicate what the students' process "weaknesses" are during synthesis. A closer look at the students' design process explains partially why they would make an analysis so early in the process: the students tended to make much more complicated designs than the experts and thus tried to avoid calculations. This raises a new question concerning the development of a design methodology for the embodiment design and detail design phases: when should analysis be introduced in the design process? If the students have access to an analysis tool from the beginning there is a risk that they stick to a bad design (one that does not respect the *basic design rules*). This issue needs to be investigated.

As stated in Section 2.1, the minimal requirements for the results presented are that they should be falsifiable, have an inner coherence and thus lack redundancy (for example by being formally described). The results have been presented in a falsifiable way, except for the interplay between synthesis, mechanical modeling and dimensioning (see Figure 4.2, p. 45). They are presented as affirmations and can be proven wrong. The design process model at the strategic level and the one at the problem solving level are presented as a sequencing of activities, which ensures coherence and non-redundancy, even if they are not described with the help of a formal representation system like IDEF0 (NIST 1993). The tactics and weaknesses form a list of the designers' behaviors related to the designers' strategies or PSP. Nor are there any redundancies. As they are elements that are independent of each other, the criterion of coherence does not apply.

If there is no redundancy *within* each of the levels 2 and 3 of the four-level study model of the designer's activity (Figure 2.1, p. 10), there is redundancy *between* these two levels. The information search process and the evaluation process concern both. It is also quite difficult to describe each design activity as a sequence of the PSP actions, because many of these actions are not performed (e.g. information search). As mentioned in Section 4.2, the information search takes place only at the beginning of the experiment. The PSP model is better understood if understood as an alternative modeling of level 2 of the four-level study model, rather than subordinated to it. Each representation provides different insights: the strategic design activity-based model gives a concrete description of the designer's activity (selection of components, etc.), while the second model allows the study of more generic activities (information search, etc.). The four-level study model of the designer's process must thus be further refined.

In Section 3.3.2.1 the literature review on the cognitive aspects of design was completed, and in Section 3.3.2.2 additional studies on embodiment design and detail design were presented. As these complements are posterior to the publication of the appended papers, the results of this study are discussed in light of these new elements in Section 5.1.1.

VDI Guideline 2223 (2004) represents an advance in the development of a support methodology for the later phases of the design process. In Section 5.1.2, the recommendations of the guideline are compared to the empirical results of this study.

### 5.1.1 The results in the light of the literature

Some characteristics of the "successful" designer established by Ehrlenspiel (1995) could not be confirmed in the cases observed: the experts did not try to generate more variants, and a good representational skill had no influence on the design quality. The relationship between the extent of the designer's solution space and the design quality has not been studied. Nevertheless, it has been observed that the experts tend to prioritize the tasks of their work; they analyze more accurately the generated solutions and thus make fewer mistakes; the experts and the seniors had better control of the process, resulting in less loss of time.

Bender (2004) reported that switching between pictorial and conceptual representation modes gave better design results. This switching is perhaps the underlying process of the PSP model presented in Figure 4.2 (p. 45): the PSP model of the embodiment design and detail design activity was presented as an interplay between synthesis and mechanical modeling of the problem, the latter activity serving to both understand the generated solution and to verify its correctness. Synthesis may very well reflect the extraction of pictorial elements present in the memory, while mechanical modeling is a more abstract, prototypical representation of elements. In order to determine if there is a correlation between this behavior and the design quality, many parameters have to be taken into account. For example, the junior switched less often and had inferior results, but one reason may be that his design was very complicated and thus difficult to analyze. A deeper study is needed to confirm or reject this assertion. The results of such a study could have an important impact on the development of a supporting methodology.

According to Günther (1998), as cited by Bender (2004, p. 95), the design quality was significantly positively correlated to the design experience and significantly negatively correlated to an emotional and regressive (tendency to flee from the problem) behavior. The impact of emotional loading to the embodiment design and detail design process has not been assessed in this study. But the importance of experience is obvious: the experts could base their activities on past experience. The regressive behavior is similar to what Bender & Blessing (2004) call adhocism and has been reported in Paper D.

Günther & Ehrlenspiel (1999) had compared designers from practice and designers with systematic education, and had found that the former skipped the first stages of the embodiment design process while the later effectively applied the phase-oriented procedure recommended by the design methodology. In the empirical study presented here, one expert had a systematic education, the two others did not and a behavior similar to that reported by Günther & Ehrlenspiel (1999) could be observed too.

Finally, following Bender's (2004) classification, one expert applied a hierarchically phase-oriented approach, and the junior student used trial and error. For the other designers, the classification was more difficult: the two other experts developed the TS and set the dimensions through experience. Their design process was almost routine-like, which could be classified as an opportunistic strategy. The last student did not try to dimension the developed system, so his strategy remains unclear. Overall it was not possible to use all the categories of such a classification. The system to design is a carrier of only one function (supporting the piston); there is also virtually no subsystem. As this classification is based on the existence of subsystems, it is difficult to use it to differentiate alternative synthesis strategies during the design of one detail.

### 5.1.2 The results in the light of VDI Guideline 2223

Presented in Section 3.2.4, VDI Guideline 2223 (2004) gives a better structure and approach to the embodiment design activity than Pahl & Beitz's (1996). The design process model is accompanied by four related methods, and Pahl & Beitz's (1996) *basic rules*, *principles* and *guidelines* have been classified as recommendations, which relativizes their importance and recognizes that they are difficult to apply in a procedural way. Moreover, there is an acknowledgement that the design process model is to be used as a guide, but that is distinct from the operational design activity — the core of this study. Moreover, as in Pahl & Beitz (1996, p. 199), it is stated that embodiment design is characterized by "a large number of iteration and recursion loops" between synthesis and analysis (VDI Guideline 2223 2004, p. 37).

At the operational level, the designer predominantly focuses on the weak points of the developed solution and their importance with regards to the requirements rather than trying to improve it. This structures the designers' process and avoids work overload. The guideline seems to rely for this point on the observations of Richter (Richter 1987), but Pahl & Beitz had already integrated it in the step "Optimize and complete form design" of their process (1996, p. 202). The explanation for the majority of corrective procedures upon generative procedures (following Dylla's (1990) classification) would be that the observation of weak points leads to correction activities rather than generation activities. The reference to Dylla's (1990) work in the guideline is not clear, however.

Another "hint" (VDI Guideline 2223 2004, p. 39) is to keep as much as possible an overview of the technical system. This limits the late discovery of incompatibility between form design elements or of unsatisfied requirements. This recommendation also comes from empirical studies (the sources are not mentioned). This hint would have been helpful to the students who participated in the experiments because they forgot from time to time the spatial constraints linked to the presence of the equipment below the piston. It is difficult to assess whether the experts had an overview of the technical system as they secured the spatial limitations at the beginning. It is not certain, however, whether this hint should be applied as is: trying to keep an overview of the TS is a cognitive burden; a regular (or opportunistic) check on the form design elements' compatibility and design requirements should be sufficient.

Finally, a systematic search for solution is emphasized when the other intuitive hints are not leading to any solution. The method of "variation" fits this purpose. This has been discussed in Section 3.2.4.

With regards to the proposals of the guideline, the support to synthesis at the operational level is still embryonic (a few hints and one method). The guideline section "operational procedure during form design" itself is very loosely structured in comparison with the "strategic procedure during form design" section (VDI Guideline 2223 2004, pp. 37-44, and pp. 17-27). The only form of description of synthesis in the guideline is Dylla (1990)'s generative/corrective procedure. The development of a fine model of synthesis, like the PSP-based model presented in Paper B, is in line with the motivation behind the guideline to further develop an operational procedure during form design. Some observed tactics like the use of standard components should be further studied to be proved useful to the designer. Finally, the concrete tasks of design (selection of components, joints, etc.) and their sequencing investigated in Paper B are not approached in the strategic procedure of the guideline, which remains relatively general. The integration of these concrete tasks into the design process model (and the relevance of such integration) should be also investigated.

With regards to the different elements presented, the focus of the *overall* research project seems to have shifted from the study of synthesis in the embodiment design and detail design phases to the study of form design in the embodiment design process. It is, however, important to recall that some design activities theoretically related to detail design, like joint preliminary dimensioning, occurred early in the observed design processes and that it is considered as a part of synthesis, in opposition to the analysis of the technical system. It is clearer than ever that the borderline between the embodiment design and detail design phase is not clear.

## 5.2 Reflections on the research approach

The pragmatic approach is not challenged by the results obtained in this study. It is not certain that the descriptive model of the embodiment design and detail design process obtained here will contribute directly to the development of a design methodology. But they are at least important for the development of design tools that would support the "natural" design activity (see e.g. Leclercq & Juchmes 2002).

As mentioned above, the four-level study model of the designer's process must be further developed. The first level remains unchanged; the design process can still be seen in a systemic perspective. But the second and third levels must now be seen as two different models of the same process. This also questions the place of the fourth level of study. It is possible that this level is to be considered as a third modeling approach of the design rather than as subordinated to levels two and three.

## 5.3 Reflections on the experimental method

The following points are discussed: choice of the method, analysis process, choice of the coding schemes, and interpretation of the results.

Verbal protocol analysis is now a largely used method for research studies that aims at the description of the design process. However alternative methods were possible: logbooks, deep interviews, etc. Sketch analysis was not performed to any great extent, although sketching is essential for embodiment design and detail design. As Franke (1985) recalled it, sketching is a powerful tool that has been quite neglected in the development of methodologies: "The art to find through free-hand sketching (Leonardo!) solution ideas or starting points for improved ideas, as soon as it is not about pure design problems, has quite fallen into oblivion." (Franke 1985, p. 915, in translation by the author) These methods can give other insights on the design process and confirm the findings by triangulation. Nevertheless, the chosen method permitted obtaining the results desired: a descriptive design process pattern that the designer follows, and its weaknesses.

The assignment corresponds to a typical embodiment design and detail design problem. However, it is only one of many kinds. Design problems in the embodiment design and detail design phases could be described in at least four dimensions: complexity, specifications, production, product branch (mechanical engineering, precision mechanical engineering, electro-mechanical engineering, structure engineering, etc.) (See Pahl & Beitz 1996, p. 4):

- Complexity. The TS to design is a simple one: a static problem with one load and two interface/contacts areas with the environment (the piston and the floor).
- Goals. There are few specifications.
- Production. The TS is to be produced in one-off batches.
- Product branch. The TS is a mechanical product.

Considering only the mechanical engineering branch, the results concern only one of at least 6 possible cases. It remains to be shown to what extent these results can be extended.

The protocol was coded by two coders simultaneously. This allowed refinements and changes of the coding scheme, and in the author's opinion, this is a necessary step at the beginning of the coding. But this did not guarantee reliability of the coding, even if there were few disagreements between the coders.

Because of the time and resources the method requires, it is very difficult to obtain valid results. Only the works by Atman et al. (1999), Bender (2004) and Fricke (1993) that used this method in the mechanical engineering design research field are known by the author to be valid. Other methods are likely to be employed for the validation of the important elements of the description of the design activity that should be validated (see Table 2.1, p. 8).

Even with reliable and valid experiments, the interpretation of the results is subjective and arbitrary. For example, all the students developed an artifact designed to take the force directly, by means of a beam. All the supports designed by the experts, on the other hand, had the shape of an arm taking the flexion created by the force.

One interpretation was that "This seems to show that students tend to reason more easily in terms of force than in terms of moment." (Motte et al. 2004) The interpretations can be the object of further investigation but are not validated *de facto* by the experiments performed. This study tried not to use the interpretation of the results, but the results themselves to model the design process (see results in Table 4.3, p. 48 and Table 4.4, p. 49).

# 6 Future research

*This licentiate thesis is just a first part of the* overall *research project presented in the introduction. The first section presents the activities necessary to achieve the* overall *research project. The second section presents new research questions that this study has fathered.*

## 6.1 Towards the completion of the *overall* research project

This thesis presented the first of many steps necessary to achieve the goal of the *overall* research project, which is **to contribute to the development of a support methodology, including necessary tools, aiming at facilitating synthesis in the later phases of the mechanical engineering design process**. The activities that should be undertaken subsequent to this thesis are the following:

- As mentioned earlier, VDI Guideline 2223 (2004) was released while this study was already at an advanced stage. The new elements of the guideline were not included in the analysis of the designers' activity. Some of those elements, together with the observations reported in this study, are important for the development of a support methodology for synthesis (see Sections 3.2.4 and 5.1.2). It seems plausible that VDI Guideline 2223 will be the starting point of any contribution to the development of a support methodology for synthesis. Thus a more thorough analysis of the guideline needs to be undertaken.
- Level 1 of the four-level study design model has not been investigated yet. To this end, a case study of an industrial project was started in January 2006.
- So far, only students (novices) and experts have been studied, but not designers (intermediates) (see Table 2.2, p. 11). Studying the former has permitted comparing two extremely different behaviors. However, the designer is the primary user of a developed design methodology in industry. It is important to study his/her characteristics and compare them to those of the novices and experts. This may be done by other means than protocol analysis.
- One delimitation was that the designer is considered to be alone while performing the synthesis activities. Nevertheless, with regards to the weaknesses illuminated in this study, for example, generation of only one or two solutions, the question can be asked whether a limited collaborative design activity would impact the design quality. Under the embodiment design and detail design phases, the time and money allocated to each designer are determined with more accuracy than for the conceptual design phase because

the design problems are more well defined, thus easier to predict. That means roughly that involving two designers in one embodiment design and detail design activity will be considered more profitable if they obtain the same design quality as the designer alone in less than half the time. Some experiments have been performed with groups of two students, and some preliminary results seem very promising: the students do not find more ideas, as was expected, but they discern and correct each other's errors, which saves a large amount of time.

- The hypothesis that synthesis can be separated from analysis has been discussed in Section 5.1. The performed experiments did not invalidate this hypothesis; however, many students would have modeled their first ideas by an FEM-based analysis tool much more quickly. Eriksson & Burman (2005) give some recommendations on how to perform analysis at the different steps of the design process. Their recommendations should be included in the development of an embodiment design and detail design process methodology. Moreover, when analysis should take over synthesis should be studied, as it seems that students would have a tendency to develop simpler and clearer designs (designs that respect the *basic rules* of *simplicity* and *clarity*) if they had to dimension them themselves.
- The two design tools described in Section 3.2.5 can support synthesis. However, the weaknesses observed during the experiments call for more easily available tools. It is possible that some of the problems induced by these weaknesses could be avoided by means of tools that control and support synthesis. As shown by the literature (see also Paper A, Section 5.2), such a support tool has the demanding requirement of not slowing the pace of designing. Specifications for non-intrusive supporting tools have to be elaborated as in Leclercq & Juchmes (2002)'s "absent interface" (the actions of the supporting tool of Leclercq & Juchmes (2002) are "triggered" by the sketch of the architect[17]) together with the study of the possible implementation of the *basic rules*, *principles*, *guidelines*, *patterns* and methods from VDI Guideline 2223 (2004).
- Level 3 of the four-level study model of the designer's activity (see Figure 2.2, p. 11) included other elements such as visualization or design knowledge (retrieval, storage and re-use). These elements also need specific studies.
- So far, the outcomes of the descriptive study of synthesis in the later phases of the design process are meant to be used in the development of a design methodology. The development of a design methodology is an iterative process. An embryo of such a design process methodology that is adapted from Olsson (1995) and that takes into account some of the elements of the

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[17] Ullman (2002) claims for a similar approach for mechanical CAD-systems.

present study, has been developed and taught to the students[18]. This methodology and its outcomes have been reported in Motte et al. (2005). A more highly developed design methodology, mainly based on VDI Guideline 2223 (2004) — if a design methodology is still seen as the best solution to support the designer's activity — should be the outcome of the *overall* research project.

## 6.2 Bases for future research

This research project has given rise to a calling into question of some fundaments of design research that could be the basis for future study.

It can be clearly stated in the light of this thesis that this work follows a tradition of the German-speaking research community in engineering design. The fact that the best help for the designer is a complete methodology based on a design process model, and defined methods and tools for each step is in line with the works of, among others, Pahl & Beitz (1996), Hubka (1996), VDI Guideline 2221 (1987). Other design process modeling approaches like those presented in Section 3.1.3 are not taken into account. The fundamental question of whether a design methodology is the best way to help and support the designer remains to be answered. There are many pros and cons. One argument for is that designers need guidance and that such a methodology can be used to plan one's work. The counter-argument is that it can never be used "as is". Franke (1985) showed for example that there is always a shift between conceptual design and embodiment design/detail design (Section 3.3.1) during the activity of designing. If the design activity at the operational level is very far from that of the design process model, then the latter has very limited use.

Maybe one aspect that explains this apparent incommensurability is the desire to develop one process model for all the possible mechanical engineering design problems. In the area of well-defined problems, nobody is trying to use a generic heuristic for chess, but rather to find specific strategies for each situation. Perhaps specific design process methodologies would be more efficient if they were specific to different types of problems.

Another aspect is that these methodologies are not presented in a flexible way (even if they are claimed to be flexible, see Pahl 2005). Presented as a procedure (a set of instructions to be strictly applied in a defined situation to obtain the sought result), it is difficult to extract from the model the important steps to perform and to discard the others.

In addition, some fundamentals of the current design process methodologies (Sections 3.1.4, 3.1.5 and 3.1.6) are now beginning to be questioned. Bender (2004), for example, has recently demonstrated that an opportunistic design process gives better design quality than a systematic-based one. Some other aspects can also be ques-

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[18] This methodology is based on a design process model with "loose" heuristics for each steps, rather than determined methods.

tioned: continuous refinement of the product, reasoning in term of working principle vs. reasoning in term of solutions, etc.

In the majority of the works reviewed, the object of design has disappeared. Visser (2004), quoting Blessing (1994, p. iii), writes: "focus on the design activity rather than on its deliverables… would be the most appropriate approach to improve design" (Visser 2004, p. 7). If developing design process models and methods based solely on the products' characteristics has led to ineffective results, focusing only on the designer may as well prevent acquiring a general view of the design process. It cannot be excluded that the designer behaves differently depending on the particular object he/she deals with. A different insight could be gained by studying both, and by describing the object of design with the help of alternative *domains* rather than by its technical characteristics and properties (*cf.* Hubka 1996's description of technical systems by their properties, pp. 143 ff). Some works are leaning in this direction. Lonchampt (2004) described the designer's activity with four elementary processes and developed four object classes to describe the objects implied in the design activity. For Hatchuel & Weil (2003), the objects manipulated can be characterized as knowledge or concept (see Section 3.1.4). These are empirical object descriptions. The question remains, however, whether these models of objects correspond to the real perception of the designer or whether they are the researcher's interpretation of the design process observed. Knowing how the designer perceives the objects he/she is manipulating can help in developing support for what he/she has difficulties to deal with.

As mentioned in Section 5.1, the vast majority of studies that aim at describing the designer's activity are explorative in nature. This kind of study is more than ever required, as it shows that the design research community humbly recognizes its lack of knowledge and understanding of the practice of design. However, after more than 20 years of explorative studies (20 years is a long time for a field that really emerged only during the last 50 years), some structure of the different facets of the design practice should appear, and a research programme prioritizing some perspectives over others should be set up. This aspect was perhaps clearer when the first descriptive studies were undertaken. Hales (1991) performed the whole development of a design project. He formulated its results in a way that could permit a comparison with further case studies (Hales 1991, p. 111). Visser (2004) goes in this direction by structuring some aspects of design, offering a synthesis of the cognitive models of the design process. The work of Bender (2004) is also known to the author to be based on a clear strategy directly oriented to further application. One of the fundamentals of design methodologies was chosen — the systematic approach — questioned in relation to cognitive aspects of design and compared to alternatives. The conclusion, statistically proved, was that an opportunistic and associative strategy was preferable to a systematic one. This result, because it is grounded, unlike to the explorative studies, can be re-used to develop further design methodologies. This research strategy seems to be the most promising one for the research field of design.

Finally, form and disposition (“Gestalt” in German) has always been at the core of the design activity in the German literature. Much of the research in Germany in the 50s, 60s and early 70s aimed at finding the principles and guidelines to give form to the details, and has been compiled in Pahl & Beitz (1996)’s work. It is thus natural that form design is the major activity of the embodiment design phase. It is not the case of the Anglo-Saxon literature, where form is just one of many design problems (French 1985), and was almost absent from earlier works (Eder & Gosling 1965; Ellinger 1968; Krick 1969). This observation questions the place and importance of form design in the later phases of the mechanical engineering design process. Is Gestalt the core of the detailing activity or one of many others?

# Glossary

There is no terminology on which everybody agrees in the research field of design. In the corpus of this thesis, some important terms have been defined formally in order to relieve the texts from unavoidable ambiguities. In order to ease the reading of this thesis, these definitions have been reproduced in this glossary. They are by no means claimed to be of a universal order, they are merely a convention of language adopted for this thesis. If the definition is taken directly from a source, the source is indicated in parentheses. Notice that Pahl & Beitz (1996) and VDI Guideline 2221 (1987) have different definitions of the term SOLUTION PRINCIPLE. Only Pahl & Beitz's (1996) definition is used in this thesis.

**ANALYSIS:** In this particular thesis, for lack of an adequate terminology, analysis regroups the design activities in which the understanding and the verification of the behavior of the TECHNICAL SYSTEM are predominant, and requires methods and tools like multibody systems analysis, structural analysis, thermal analysis, electrical analysis, magnetic analysis and computational fluid dynamics. Analysis is defined in opposition to SYNTHESIS, which represents the design activities where the solution generation is predominant.

**BASIC RULES:** General recommendations for the designer which have proved successful in FORM DESIGN tasks (VDI Guideline 2223 2004). The basic rules appear to be fundamental to all embodiment design PRINCIPLES and GUIDELINES (Pahl & Beitz 1996, p. 207). The basic rules are *simplicity* (e.g. few components, simple shapes), *clarity* (facilitates the prediction of the TS behavior) and *safety*.

**CONCEPTUAL DESIGN PHASE:** Phase of clarification of the design task and of development of a concept in which at least the overall SOLUTION PRINCIPLE of the product-to-be is established.

**DESIGN:** 1) The activity itself (definition left to the reader's preference). 2) The result of the design activity; at the end of the embodiment design and detail design phases, a TECHNICAL SYSTEM ready to be produced. 3) The term "design" when evoked as an object of study encompasses all design disciplines: ENGINEERING DESIGN (which also encompasses MECHANICAL ENGINEERING DESIGN), industrial design, and architecture. In this document, the term "design" is used for mechanical engineering design, whenever this denomination is unambiguous.

**DESIGN CATALOGUE:** Design catalogues are collections of known and proven design solutions.

**DESIGN METHODOLOGY:** A design methodology is composed of a DESIGN PROCESS MODEL that shows a generic set of activities, and their related METHODS and TOOLS.

**DESIGN PROCESS:** Totality of the design activities performed to develop a TECHNICAL SYSTEM (from VDI Guideline 2221 1987).

**DESIGN PROCESS MODEL:** Set of generic activities (indicating "what" to do), each of which can be realized by following a METHOD (showing "how" to do it) and with the support of design TOOLS.

**DESIGN QUALITY:** Quality of the final solution of the design activity (see definition 2 of DESIGN). For the embodiment design and detail design phases, the design quality can be measured: a) correspondence between the criteria and the final solution; b) the accuracy of the dimensioning calculations (in other words, if the TECHNICAL SYSTEM will hold) (Motte et al. 2005).

**DESIGN RULES:** Synonym of GUIDELINES (VDI Guideline 2223 2004). Not used in this thesis.

**EMBODIMENT DESIGN AND DETAIL DESIGN PHASES:** Phases of transformation of the product concept into a TECHNICAL SYSTEM ready to be produced. Comprises the FORM DESIGN and the planning, control and monitoring of the form design process.

**ENGINEERING DESIGN:** 1) Constitutes that field of design whose purpose is to deal with the technical aspects of the product-to-be. 2) The term "engineering design", when evoked as an object of study encompasses MECHANICAL ENGINEERING DESIGN but does not encompass such design disciplines as industrial design and architecture. See also definition 3 of DESIGN.

**ENGINEERING DESIGN PROCESS:** Comprises all the engineering design activities that aim at developing a product from the perceived need to the necessary technical documentation required for production.

**FORM DESIGN:** Activity during which the designer establishes form and material properties of the FORM DESIGN ELEMENTS (VDI Guideline 2223 2004).

**FORM DESIGN ELEMENTS:** Collective term for areas [surfaces] of components parts, form elements, component parts and combination of parts.

**FORM PATTERNS:** Form patterns are divided into TYPES and STYLES OF CONSTRUCTION. For the FORM DESIGN, they are models that the designer can follow and with which he/she can appropriately restrict the enormous variety of variants (VDI Guideline 2223 2004, p. 64).

**FUNCTION:** Relationship, described without regards to the solution, between input, output and state variable of the technical system.

**FUNCTION CARRIER:** Technical object to which a FUNCTION can be assigned (VDI Guideline 2221 1987). Following the different moments in the design process, this technical object can be in the form of a WORKING PRINCIPLE, a SOLUTION PRINCIPLE, or a concrete detail.

**GUIDELINES:** Instructions for the appropriate FORM DESIGN of TECHNICAL SYSTEMS (VDI Guideline 2223 2004).

**HEURISTIC:** Known procedure that gave the best results for a specific problem.

**MECHANICAL ENGINEERING DESIGN:** Constitutes that field of ENGINEERING DESIGN whose purpose is to deal with those products or parts of products in which the WORKING PRINCIPLES are based on the laws of mechanics.

**MECHANICAL ENGINEERING DESIGN PROCESS:** Comprises all the activities related to mechanical engineering that aim at developing a product from the perceived need to the necessary technical documentation required for production.

**METHOD:** Operational procedure to achieve a certain goal.

**PHASE:** A set of related activities. Can be decomposed in STEPS.

**PHYSICAL EFFECT:** A repeatable, predictable occurrence of a physical nature (VDI Guideline 2221 1987).

**PRINCIPLE SOLUTION:** Term used only in VDI Guideline 2221 (1987). Synonym of Pahl & Beitz (1996)'s definition of SOLUTION PRINCIPLE. Not used in this document.

**PRINCIPLES:** Strategies, which under certain preconditions lead to an appropriate form (VDI Guideline 2223 2004).

**PROBLEM:** A problem is a gap between an Observed State ($S_o$) and a Desired State ($S_d$), $S_o \neq S_d$, given a set of constraints. The procedure to apply in order to get to the desired state may be unknown; $S_o$ and $S_d$ may need to be refined and can change over time.

**PROBLEM-SOLVING PROCESS (PSP):** Process whose aim is to transform $S_o \neq S_d$ into a satisfactory solution that will lead to $S_o' \approx S_d'$ ($S_o$: Observed State, $S_d$: Desired State).

**PROCESS:** Set of activities performed towards the fulfillment of a certain goal.

**SOLUTION PRINCIPLE:** 1) Adaptation of the WORKING PRINCIPLE to the particular TECHNICAL SYSTEM or sub-system of this technical system. This can involve preliminary dimensioning and scaling or deeper analyses: the result is thus the solution principle (from Pahl & Beitz 1996). 2) Synonym of WORKING PRINCIPLE (VDI Guideline 2221 1987). This second definition is not used in this document.

**STAGE:** Synonym of PHASE in this document.

**STEP:** An individual activity within a PHASE.

**STYLE OF CONSTRUCTION:** Typical basic forms of products that have been defined in accordance with specific industrial sectors or applications, for example housings (VDI Guideline 2223 2004).

**SYNTHESIS:** Retrieval and comparison of the relevant knowledge (mechanical, technical…) with the current design problem, [and] putting together of the elements to fulfill the requirement from the design problem at hand. Synthesis regroups the design activities where the solution generation is predominant, in opposition to ANALYSIS, which regroups the design activities where verification is predominant.

**TECHNICAL SYSTEM (TS):** Set of ordered and connected technical elements related to their environment by inputs and outputs at the system boundary (VDI Guideline 2221 1987).

**TOOL:** A tool assists the designer in performing his activity. Some specific tools for SYNTHESIS are topology optimization and DESIGN CATALOGUES.

**TYPE OF CONSTRUCTION:** A TECHNICAL SYSTEM always belongs to a certain type defined by its characteristics (e.g. lightweight, modular, mass-produced) that indicate directly or indirectly form and material properties (VDI Guideline 2223 2004, p. 67).

**WORKING PRINCIPLE:** Combination of a PHYSICAL EFFECT together with geometry and material (Pahl & Beitz 1996, p. 41).

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# Appended Papers

# Paper A

## The Cognitive Aspects of the Engineering Design Activity – A Literature Survey

**Motte, D. & Bjärnemo, R.**

*Tools and Methods of Competitive Engineering Conference*
*TMCE'04*, Lausanne, 2004

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# THE COGNITIVE ASPECTS OF THE ENGINEERING DESIGN ACTIVITY – A LITERATURE SURVEY

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## ABSTRACT

*This literature survey aims at representing the current research on the cognitive aspects of the design activity, with an emphasis on problem-solving processes. The study is based on the selection of about sixty papers and books on the subject. The principal parameters of the study were defined as follows: general topics of the works, objects of the works, cognitive approaches, research results, study methods. The findings from this survey are: Most of the studies concern design theory, and then design support and education; They focus mainly on the conceptual design phase; The foremost cognitive aspect studied is problem solving, but knowledge, imagery and memory are also considered; The results of the reviewed papers confirm the validity of prescriptive methods for the design process, but there is a felt need for acknowledgement of the design activity constraints induced by cognitive limitations; The methods employed in most experiments are based on verbal protocol analysis and sketch analysis. The most important findings of this survey are that research should be extended to new areas, such as: Research on the cognitive aspects of the designer in the embodiment and detail design phases; Implementation of the research findings in current design practice, to improve the design process; Research of the origins of expert knowledge.*

## KEYWORDS

Design process, conceptual design, problem-solving process, cognitive aspects, verbal protocol analysis, literature survey.

## 1. INTRODUCTION

As summarized in Pahl, G. et al. (1999b), when engineering design stopped being considered as “an artistic activity”, design methodologies could be developed. Special efforts have since been striving towards normative design procedures, aiming to rationalize and optimize the development of technical artifacts. Methods have been developed for the conceptual as well as for the embodiment and detailed design phases; requirements for education, experience, knowledge, reasoning and problem solving ability of the designer have been stated (e.g. Hubka, V., 1976/1982; Pahl, G. & Beitz, W., 1977/1996[1]). This has resulted in substantial improvements in terms of costs, shorter lead times and higher product quality. However, systematically or based on best practices, present methods have been focusing on the product technologies, thus neglecting the importance and impact of the human factor — the designer. Initiated by the increased importance of the cognitive sciences, from psychology to artificial intelligence, the designer’s way of reasoning has attracted increasing attention during recent decades. It is a widely accepted assertion that the very nature of the design process is considered to be a problem-solving activity: understanding the task, generating solutions, evaluating and selecting them.

This paper is a survey that aims at representing the state-of-the-art of the research on cognitive aspects of the design activity. The designer’s problem-solving process is emphasized. The method for the survey is briefly described in a first part. This is followed by a summary of the relevant problem-solving aspects in

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[1] The second date of two separated by a slash mark indicates a reference where English translation is available.

design. In the third part, a representation of the current research in this area is developed, and a review of recent years of conjoint research between engineering design and cognitive psychology is presented. The last part reflects on the findings and proposes future paths of research.

## 2. METHOD

A loosely structured method was adopted for this review, similar to that used by Krishnan, V. & Ulrich, K. T. (2001) in “Product Development Decision: A Review of the Literature”. As a first step, we built a superset of papers related to cognitive psychology and design. We did this by searching in the university database Elin by using keywords. Elin includes among others the following journals and conferences: *Research in Engineering Design*, *Design Studies*, *Automation in Construction*, *Frontiers in Education Conference*, *Management Science*, and the *Journal of Product Innovation Management*. The titles, then the abstracts, of the papers found narrowed the number of papers to a first set. Next we browsed the table of contents of the 8 journals that appear most frequently in the selected articles. Finally, the reading of each paper led us to the referenced articles that seemed to be of importance for the domain study.

Parallel to this task, the findings in cognitive psychology relevant to the problem-solving process in the design activity were picked out, both from the cognitive psychology literature (e.g. Sternberg, R.J., 1994) and from engineering design works (e.g. Pahl, G. & Beitz, W., 1996, p. 46-60). This is presented in the next section.

The articles that were found relevant to the survey were classified as follows: 1) The scope of the work; 2) The design process concerned; 3) The models from cognitive psychology used; 4) The findings; 5) The research methods used. They are presented in section 4.

## 3. PROBLEM-SOLVING PROCESS (PSP)

The aim of this section is to summarize the well-recognized findings on problem solving in cognitive psychology that are relevant to the study of the design activity.

### 3.1. PSP in cognitive psychology

Since psychology became a science, problem solving has been studied frequently; Dominwski, R. L. and Bourne, L. E. (1994) give an overview of the research up to the 60s, whereas Ericsson, K. A. and Hastie, R. (1994) give insights into the involvement of cognitive psychology in problem solving.

The breakthrough in the study of problem solving in psychology occurred when Newell, A., Shaw, J. C. and Simon, H. A. (1958) proposed a computer program for modeling human thought. Formalized in Newell, A. & Simon, H. A. (1972), problem solving took the shape that serves as a basis now for most of the modeling: the problem, a gap between an initial state and a goal state, can be represented as a problem space (containing all the problem states) that must be searched using methods or techniques of problem solving: algorithms and heuristics. While an algorithm is a rule that correctly generates the solution to a problem, given sufficient time and effort, a heuristic “refers to a rule of thumb or general strategy that may lead to a solution reasonably quickly” (Kellogg R. T., 1995). Hubka, V. worked on heuristics in design (see Hubka, V. & Eder, W. E., 1992/1996), illustrating general techniques. Todd, P. M. & Gigerenzer, G. (2001) argue that simple, everyday-life heuristics may lead to good results in less time than complex ones; however, dedicated heuristics remain more efficient.

In conceptual design, strategies often enhance the generation of numerous ideas by using the so-called creative solving processes (see VanGundy, A., 1981); this is underpinned by the use of a systematic approach, decomposing the technical system, looking at a great number of potential sources of concepts, then trying to combine the concepts of each subsystem. The problem-solving process in conceptual design is of the “task-understanding-solution-generation-evaluation” type, because emphasis is placed on the information search (the problem is ill-defined in conceptual design), the great number of alternatives that are generated and the difficulty and importance of evaluating them.

Basic rules (*simplicity*, *clarity* and *safety*) and principles in embodiment and detail design are heuristics. Although equivalent, a PSP model that underlies the embodiment design may rather be an “analysis-synthesis-evaluation” type of process than “task-understanding-solution-generation-evaluation” described above. This model focuses on the rigorous study of all elements of the problem and their interrelations (analysis), and on the combination, or composition, of sub-solutions, to create an overall functioning system (synthesis). This indicates that the abilities and experience required in problem solving can differ for embodiment design, detail design and conceptual design. The problem space is different as well: the initial and goal states of an embodiment design are relatively well known (even better in detail design), because of the existence of the artifact concept. In conceptual design, they are often unclear and have to be constructed by the design team. The solution in embodiment design and detail design has a different structure: many features (all in detail design) of the product have to be fixed, not found, and designers no longer work with intervals of product parameters value.

## 3.2. Knowledge

Knowledge elements, and knowledge retrieval and use, are of major importance in design.

The knowledge elements are the mental representations or sets of mental representations of what we know about objects or events. Many structures of the elements have been developed. Models for objects are the classification of similar instances in categories. The most familiar have been the prototype (a concept with a number of separate features, each with some weight; each instance can be recognized comparing its features to prototypes), combined with 'the exemplar view' (explaining the prototype-like effect: recognition of similar instances that share only a few features with the prototype). On the design level, Condoor, S. S. et al. (1992) have exploited this view. An extensive review of concepts and categories in cognitive psychology has been made by Ross, H. R. & Spalding, T. L. (1994). This aspect affects the learning in design that constitutes the creation of categories.

More complex models have been developed that include events associated with objects. The most broadly used is the schema (the *prototype* is a kind a schema; see McNamara, T. P., 1994, for other models). Many definitions exist; schemata can be seen as structures containing sequences of events, "prepackaged expectations and ways of interpreting" (Chafe, W. L., 1990, p. 80 in Kellogg, R. T., 1995). In the pattern-action rules, the basic thinking processes that operate during problem solving (like induction and deduction) are elementary operations that allow manipulation of knowledge elements. The skilled problem solvers, or experts, proceed in a different manner: they rely on previously memorized solution schemata (i.e. particular memorized procedures). When a person is faced with a problem, and recognizes that it is a specific case of a general, previously encountered, problem, that person then simply applies the learned rules that will lead to the solution, without working backwards as novices do (Hunt, E., 1994).

The distinction between novices and experts is stressed here. It would be of great importance to look at how experts use the basic rules, guidelines and principles of embodiment design. In contrast to conceptual design, where knowledge has to be broad and interdisciplinary, the knowledge in embodiment and detail design is very specific. That can play a role in prototype formation, and in knowledge retrieval and use.

Another important matter related to knowledge is the mental imagery, concerned with the issue of how information is represented in memory (Solso, R. L., 1988). In design, especially form giving, the visual aspects are important, and progress in that area will stress development based on sketching, for example. This connects to knowledge retrieval, which occurs through pattern recognition, where visual information is of great importance. Recognizing forms and attributes, it is possible to come back to the prototype of the observed instances (Solso, R. L., 1988).

## 3.3. Complementary domains in cognitive psychology

Considered as a high-level cognitive process, problem solving is thus related to many other fields, especially memory, thinking processes or pattern-action rules, intelligence, and creativity. Some of them, interesting for a design theory, may however be specific neither to embodiment design nor to detail design.

Thinking processes concern mainly the studies of induction (Bisanz, J. et al., 1994) and deduction (Rips 1994). Research studies in intelligence are still in a maturation phase (Solso, R. L., 1988). These areas are still on a too abstract level for applications concerning the design activity.

Memory models are very important for problem solving because they explain some limitations of the human being. If the long-term memory has a virtually unlimited capacity, the short-term memory has a buffer that cannot contain more than 7±2 items at a time (Miller, G. A., 1956), and for a limited moment, around 12 s. This explains the knowledge model of schemata – a schema being considered as one item – and also emphasizes the importance of external support to memory (e.g. sketches, writing, speaking). These supports have been the subjects of extensive research in conceptual design (especially sketching in architectural design), as presented in the following section.

Creativity is “the ability to produce work that is both novel and appropriate” (Lubart, T. I., 1994[2]). In that sense, creativity is needed and common to all design activities. There is no unified theory about creativity, nor has great progress been made during the past twenty years (Solso, R. L., 1988). The most generally accepted creative process model is that of Wallas, G., from 1926, who describes it in 4 stages: 1) Preparation: formulating the problem and making initial attempts to solve it; 2) Incubation: leaving the problem while considering other things; 3) Illumination: achieving insights into the problem; 4) Verification. Even if the internal mechanisms of creativity remain unknown, numerous studies have been done in design in order to provoke and model creativity. If creativity is needed at all stages of the design process, things change when we are considering first the relative importance of the creativity for each phase, then the ‘quantity’ of creative findings. On a conceptual level, creativity will be emphasized: the start of a new design comes from a need, i.e. a lack, expressed by a client or the company itself, which only something new can fulfill. Moreover, in order not to focus on one solution, many concepts will have to be found. On the other hand, one of the guidelines of embodiment and detail design is the re-use of designs or use of standards, for reasons of performances, delays and costs (and that is confirmed by the basic rules of simplicity, clarity and safety). Matousek, R. (1963, p. 65) recalls that proven designs are well thought out and changes must be undertaken with full knowledge of facts. Thus the task of the designer is more to focus on retrieval, before producing something totally new.

## 4. CURRENT RESEARCH ON COGNITIVE ASPECTS OF DESIGN

The previous section presented a study of the contributions that cognitive psychology brings to the study of the design activity. In this section, the results of a survey of journal articles from the last five years are presented—with some major papers from the last ten years—on cognitive aspects in design. The current research is represented in Table 1.

### 4.1. General scopes of the studies

Some argue that the description of the design process in terms of cognitive processes must serve as a basis for a design theory (Dörner, D., 1999; Christiaans, H. H. C. M. & Dorst, K. H., 1992). Many studies aim as well at improving design process methodologies (Pahl, G. et al., 1999a; 1999b; Fricke, G., 1999; Hacker, W., 1997). The aims of other research studies are towards improvement of the whole design process (Pahl, G. et al., 1999a; 1999b; Condoor, S. S. et al., 1992).

Some authors emphasize the importance of external design support to overcome human cognitive limitations. Sketching is of great importance (Römer, A. et al., 2000; Kavakli, M. & Gero, J. S., 2001; Ullman, D. G., 2002). Römer, A. et al. (2000) suggest prototyping as another good means. Ullman, D. G. (2002) and Shah, J. J. et al. (1994) insist on the need to re-think CAD systems. Ball, L. J. et al. (1998) propose a support system based on artificial intelligence.

Some articles are dedicated to design education (Atman, C. J. et al., 1999, Adams, R. S. & Atman, C. J., 1999).

Some have theoretical implications for cognitive psychology: Goel, V. & Pirolli, P. (1992) detected invariant features in problem solving that are common to the domains within design.

### 4.2. The design processes concerned

Only a few papers dealt with embodiment and detail design. Most of them study problem solving in a “task-understanding-solution-generating-evaluation” way rather than “analysis-synthesis-evaluation”. The problems to solve by the subjects of experiments are on a conceptual level (see Atman, C. J. et al., 1999; Adams, C. J. & Atman, C. J., 1999; Fricke, G., 1999; Hacker, W., 1997; Shah, J. J. et al., 1994; Christiaans, H. H. C. M. & Dorst, K. H., 1992; Pahl, G. et al., 1999 for a description of research studies).

Römer, A. et al. (2000), however, tested students on the benefits of an external support for a design to embody. Fricke, G. (1999) deals partly with embodiment and detail design, but the study focuses mainly on task clarification. There is clearly a lack of studies focusing exclusively on embodiment or detail design.

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[2] This article is also a review of research in creativity in cognitive psychology.

**Table 1. Survey of studies on cognitive aspects of design**

| | |
|---|---|
| General scopes of the studies | Design theory<br>Design process methodologies<br>Design process as a whole<br>Design supports<br>Design Education<br>Theoretical implications on cognitive psychology |
| Objects of the studies | Clarification of the task<br>Conceptual design<br>Problem understanding<br>Idea generation<br>Evaluation<br>Design supports<br>Sketching<br>CAD system<br>AI systems<br>Designer's characteristics |
| Cognitive approaches | Problem solving<br>Problem space<br>Heuristics<br>Thinking process<br>Knowledge-based models<br>Retrieval and use of information<br>Knowledge representation: concepts and categories, schema<br>Imagery<br>Memory<br>Human intelligence<br>Artificial intelligence |
| Findings for problem solving in the process of design | Confirmation of the validity of prescriptive methods<br>but<br>Claim for an acknowledgement of findings in cognitive psychology:<br>Dealing with early appearance and persistence of a kernel idea<br>Failure to search for alternative solution<br>Design fixation (inclination to stick with early satisficing solutions)<br>Superficial assessment, subjective judgment<br>Hypothesis of inhibitory memory processes subsequent to recognition of familiar solution<br>Lack of flexibility in designer's thinking behavior<br>Claim for design supports, as extensions of the designer<br>Sketching<br>Improving 3D system<br>Intelligent systems for retrieval and reuse |
| Study Methods | Experiments: Study of the cognitive aspects of individuals during design:<br>Verbal protocol analysis and Sketch analysis<br>Quantitative study |

Some papers go beyond the design process. This is the case when the work was not attached to the task. Eisentraut, R. (1999) stated that a designer does not tend to change a problem solving "style" (uses the same methodology) when facing a new problem. Pahl, G. et al. (1999a) reported works on "significance of personal characteristics". Finally, some articles consider the possibility of treating different design sciences as a whole, considering for example the possible commonalities between architectural design, mechanical design, programming and electronic design (Goel, V. & Pirolli, P., 1992, Adams, C. J. & Atman, C. J., 1999, Ball, L. J. et al., 1998, Suwa, M. et al., 1998, Kavakli, M. & Gero, J. S., 2001, 2002).

## 4.3. Cognitive approaches

The articles have studied problem solving in design process from different points of view: some consider the problem-solving process directly; others study it through knowledge, imagery, memory, or intelligence; still others opt for a hybrid approach.

Fricke, G. (1999) studied the ability of designers to deal with variously precise design problems. Thus special attention is directed towards strategies and heuristics adopted in clarifying the task, generating ideas and evaluating them. Two important parameters are technical knowledge and heuristic competence (ability to plan and control the problem-solving process for new types of problems). Hacker (1997) reports that emphasis must be put on the problem-solving phases. In Adams, C. J. & Atman, C. J. (1999), a new model of PSP is developed for explaining the transitions between different steps of the problem-solving process: this was explained by transitions between cognitive activities considered as information processing activities and decisions/action activities. Pahl, G. et al. (1999), reporting 12 years of empirical studies in Germany, applied the results to the design process: they are largely based on cognitive activities underlying the problem-solving process. A strong emphasis is also placed on the search through problem space and the strategies or heuristics used by the designer to arrive at a solution. Eisentraut, R. (1999) also studied the general strategies of designers. The notion of problem space has now been widely accepted and is even integrated as a theoretical structure for explication of the general process of designing (e.g. Dym, C. L. & Little, P., 2000, pp. 135–146). A very few, like Dörner, D. (1999), considered the forms of thinking inherent in PSP. Hacker, W. quotes Pahl, G. (1994) regarding the field of intelligence.

Other research studies are connected to knowledge. Condoor, S. S. et al. (1992) urged the acknowledgement of categories and concept models of knowledge. The formation, recognition, and retrieval of concepts and objects are important in design. However, most of the other studies focus rather on retrieval of design actions, using more complex models like the schema (Christiaans, H. H. C. M. & Dorst, K. H., 1992, Ball, L. J., 1998).

Imagery, related to the activity of sketching, attracts the attention of many scientists. That was tackled in the research framework of Pahl, G. et al. (1999); Kavakli, M. & Gero, J. S. (2001,2002) use the mental imagery theory to describe cognitive activities executed while sketching. Suwa, M. et al. (1998) and Römer, A. et al. (2000) also use imagery but focus more on sketching as a means to relieve the load on immediate memory, to retrieve knowledge elements, and to trigger thinking processes. Römer, A. et al. (2000) insist on the importance of external supports, not only sketching but also modeling and prototyping. Ullman, D. G. (2002) stresses only the memory model to show the need of sketching and the need for CAD systems to be adapted to human memory systems, i.e. to permit drafting as fast as sketching.

Finally, some studies concern a combination of cognition domains, like Ball, L. J. et al. (1998), who looked at the problem-solving phases, as well as memory and knowledge. Hacker, W. (1997), listing the contributions of cognitive ergonomics, invokes PSP, imagery and memory.

## 4.4. Findings

Concerning the design process, Atman, C. J. et al. (1999) and Adams, C. J. & Atman, C. J. (1999) confirm the validity of prescriptive methods in the design process. The students who considered more alternatives had a better result quality. Other studies, however, temper these findings. Designers observing the prescribed methodologies will be on average more successful than those who do not (Pahl, G. et al., 1999), but prescriptive models “are in conflict with natural cognitive models” as Condoor, S. S. et al. (1992, p. 277) claim. These authors list human behaviors and characteristics that contradict rigid procedures: Early appearance and persistence of a core idea; Lack of generation of alternatives; Design fixation; Lack of flexibility; Subjective judgment; Reluctance to change after a design is made; “satisficing”. Ball, L. J. et al. (1998, p. 213) complete the picture: failure to search for alternative solutions, marked inclination to stick with early “satisficing” solutions, only superficial modeling and assessment of competing alternatives when such options are actually considered. The claim is that these “human specificities” should be integrated in methodologies. Fricke, G. (1999) noticed that good designers did not suppress their first solution ideas, but did not exploit them until the clarification of the task was complete. His conclusion is that this should be practiced in teaching.

Simon, H. A. (1996, p. 119) defined the term “satisficing” to refer to procedures that search “good or satisfactory solutions instead of optimal ones”. This concept explains why a designer can stop searching, having only the “feeling” that he has reached a sufficient solution or set of solutions (Pahl, G. et al., 1999a, p. 484). Sometimes, solution search stops even without a satisficing one; another phenomenon may be behind this. Ball, L. J. (1998) uses the hypothesis that an inhibitory memory process can arise subsequent to the recognition-based emergence of a familiar design solution. Pahl, G. et al. (1999a) report that research showed that various approaches lead to good solutions; that sub-problem-oriented (opportunistic) procedures are also successful depending on the problem; that methodology is useful but never rigorously followed, and that there is a need for more flexibility in methodology, but not in an individual and situation-oriented manner. Eisentraut, R. (1999)

confirms this view. The way humans solve problems is not really flexible, whatever the problem may be.

The general conclusion from these findings is that 'biases' introduced by human cognition have to be taught, so that the students will be aware of them, and that procedures should be employed less rigorously.

The next point concerns the external supports to help embody artifacts. Ullman, D. G. (2002) emphasizes sketches to relieve strain on the working memory, and improvement of CAD systems to adapt to a designer's speed of thinking. Römer, A. et al. (2000) strengthen the case for psychological research: sketching gives supportive aid for memory as well as for thinking. Suwa, M. et al. (1998)'s experiments, like Römer, A.'s, show that sketches serve as an external memory, as a cue for association of ideas, and "as a physical setting on which thoughts are constructed". Ball, L. J. et al. (1998) propose an interface agent from AI linked to a knowledge management tool for generation and evaluation of concepts. This agent focuses not only on solution findings but on design process re-use as well.

Davies, S. P., (1995) however, poses a strong restriction concerning support design systems based on active (manual or verbal) expressions of the design process. Indeed, the designers have to describe their own design process to feed and activate such systems, which can in turn retrieve former designs. But, having to describe the design activity is not a part of this activity itself. The description given by participants in a study based on verbalization can introduce a bias. Moreover, that "may impose a structure upon that process which would otherwise be absent." (1995, p. 113). This partly explains problems encountered by such a design support system (Lambell, N. J. et al., 2000, pp. 452-453).

The differences between novices, intermediates, and experts are significant. The participants in the experiments are generally classified as follows: novices or freshmen (they had just begun learning design), intermediates or "senior" students (last-year students or just graduated), and experts (from 3 to 25 years' experience). Atman, C. J. et al. (1999) recorded better quality from the last-year students. Christiaans, H. H. C. M. & Dorst, K. H. (1992) report as well that 2nd-year students were not asking any questions, accepting the given specifications as sufficient; more experienced designers gathered more information. Concerning design procedures, experts tend to do more transition between design steps (Adams, C. J. & Atman, C. J., 1999; Atman, C. J. et al., 1999; Christiaans, H. H. C. M. & Dorst, K. H., 1992; Pahl, G. et al., 1999). It has been noticed that experts, with better knowledge, even tended to operate opportunistic strategies, i.e. could follow sub-problem-oriented procedures with success instead of applying a systematic approach at all design steps. Others, like Davies (1995), object that an expert's behavior is broadly top-down with local opportunistic episodes. Fricke, G. (1999) found that good designers have a balanced approach. According to Ball, L. J. (1997), a designer only uses an opportunistic strategy when faced with "difficulties, uncertainty, and design impasses".

The expert, however, has no special capacities. It has been shown that the domain-specific knowledge (developed schemata) makes the expert, and not unusual abilities (Christiaans, H. H. C. M. & Dorst, K. H., 1992). Experts cannot be differentiated in terms of intelligence determined by classical tests (Pahl, G., 1994 quoted by Hacker, W., 1997, p. 1089). Other studies showed that ideas are found by retrieval rather than by creativity (Pahl, G., 1999). Furthermore, studying sketches (Kavakli, M. & Gero, J. S., 2001; 2002), it has been observed that cognitive activities of the novice dropped at some moment, which signifies unfocused attention. Moreover, the expert's cognitive activity while sketching can be modeled as tree-structured, while the novice has more categories of activity that are difficult to relate to each other. More structured design strategies and focus could be the reason why experts have high performance. But Kavakli, M. & Gero, J. S. raise the following question: could unfocused attention and poorly structured activity lead to more novelty? Unfocused attention might make remote idea associations more accessible (like the incubation step in the creativity process); ambiguity in sketches can play a similar role.

Knowing the expert's reasoning, knowledge structure and retrieval is a "must study" for development of expert systems and improvement of education.

Finally, concerning education, Pahl, G. et al. (1999), Fricke, G. (1999), Condoor, S. S. et al. (1992) argue for an acknowledgment of, and teaching, the limited human capacity to follow rigid procedures. The work of Adams, C. J. & Atman, C. J. (1999) is oriented towards the teaching of design. Research on teaching design based on cognitive aspects is in fact just in its infancy.

### 4.5. Methods used

The papers reviewed remarkably used slightly different kinds of methods, which can be gathered under the heading of Verbal Protocol Analysis (VPA) and sketch analysis, inspired by cognitive psychology methods.

Basically described in Ericsson, K. A. & Simon, H. A. (1993), VPA consists of asking the participants "to think aloud" during a design process, and then studying their descriptions. However, the protocols include not only recorded documents, but sketches and notes of the designer as well. The participants are sometimes recorded on video and afterwards transcribed (Fricke, G., 1999). Christiaans, H. H. C. M. & Dorst, K. H. (1992) give students a preliminary exercise for training. Then a scheme for coding designers' cognitive actions, based on a preliminary analysis of protocol content (Ball, L. J. et al., 1998), is created (as in Suwa, M. et al., 1998; Gero, J. S. & McNeill, T., 1998) or modified (Kavakli, M. & Gero, J. S., 2001; 2002), depending on the scope of the study. The categories of the coding schemes and the segmentations of the protocol are up by the authors, but once the instantiations have been realized, a statistical treatment of the results can be made.

Dorst, K. H. & Dijkhuis, J. (1995) discussed two paradigms for describing design activity. The process-oriented approach focuses on the relations between the designers and the design process; the categories of the coding schemes are in terms of design stages, information processed, and the artifact (e.g. Purcell, T. et al., 1996; Atman, C. J. et al., 1999). Most of the methods employed by the articles reviewed belong to "design as a process of reflection-in-action" (1995, p. 262). The aim is to be closer to the designer's cognitive activities in order to observe, for example, the influence of knowledge or memory on the design actions, as in Suwa, M. et al. (1998) or Kavakli, M. & Gero, J. S. (2001; 2002). Dorst, K. H. & Dijkhuis, J. (1995) suggest that problem-solving processes where the initial and final states, as well as the strategy, are relatively clearcan be studied with the first approach. This can be enhanced for some of the scopes of study of embodiment and detail design (how are the designers using the basic rules, guidelines and principles, for example), while the others have to be approached by closer studies of the cognitive activities.

Davies, S. P. (1995) warns against a study solely based on verbalization. His study reveals strong indications that verbal descriptions may not map well onto behavior, and even that describing the design activity may affect the process itself. The hypotheses that can explain this fact are first that VPA was originally used for well-defined problems. There is a need to show that this method is accurate for more complex studies. The designer will naturally tend to avoid saying that he or she is acting irrationally, if this is the case, giving a rational justification post hoc. The act of verbalization can change the focus; language itself can impose its own structure. This study suggests that VPA should be coupled with visual protocols by means of video recording. In a prior publication, Shah, J. J. et al. (1994, p. 213) had already identified such criticisms, and developed a non-intrusive method, with two designers working co-operatively, which would "provide a 'natural' setting for articulating what is going on in their (subjects) minds". But even so, some problems remain (e.g. do the designers describe all their thinking processes?), and comparison studies as in Davies, S. P. (1995) remain to be carried out.

## 5. DISCUSSION

The aim of this section is to reflect on the research area and discuss future directions that can be explored.

### 5.1. Embodiment and detail design

Most of the literature refers implicitly to the cognitive aspects of the design activity of the conceptual design phase. This may be due to the fact that, at a conceptual level, the problems given to the designers are ill-defined and potentially cause great biases in the research on the solutions. Moreover, conceptual design is characterized by a strong demand on creativity and the attempt to understand it. The stakes of this phase are high for the further development of a product. Finally, some studies hypothesize that the designer is subject to the same human-dependent 'biases' during any design activity, whatever the design process phase.

However, this assumption needs to be examined. Some findings may not be compatible with, or not answer to, the specificities of embodiment design and detail design. It was previously mentioned that the problem-solving process is rather of the type "analysis-synthesis-evaluation" than "task-understanding-solution-generation-evaluation". Moreover, embodiment design is based on basic rules: *simplicity*, *clarity* and *safety* (see e.g. Pahl, G. & Beitz, W., 1997/1996; Sundström, J. et al., 2000). These basic rules are supported by *guidelines* based on the constraints of the design, defined during conceptual design. They cover the range of "design for X" as well as ways of dealing with some physical and natural effects like corrosion, wear and thermal expansions. Finally, rules and guidelines are complemented by *principles*, kinds of 'laws' that have been verified by practice and that facilitate the design (Matousek, R., 1963; Leyer, A., 1964; French, M. J., 1998; Pahl, G. & Beitz, W. 1977/1996).

These specificities — basic rules, guidelines and principles —— certainly have an impact on the problem-solving process used by the designer. These rules can be questioned: when and how does the expert design with simplicity or clarity? How to characterize them? Does he seek some support from the guidelines and have in mind the principles during effective embodying and detailing? Is there any human limitation to their application? What tool can be offered to support the embodying and detailing design processes? How are the differences between novices and experts expressed? What characterizes an expert in embodiment and detail design?

Teaching embodiment and detail design is also involved, thus touching on the structure of domain-specific knowledge. Questions can be asked about the efficiency of the "right-or-wrong" examples to provide the most adequate basis for learning (already mentioned in Matousek, R. 1963). Likewise, are the empirically based guidelines (simplicity, clarity, safety) satisfactory for the students?

## 5.2. Implementation of the findings

### Improvement of the design process

Among the discoveries made while studying the cognitive aspects of the design activity, only very few are currently used beyond this research area. The concept of problem space is one such discovery: it serves when modeling the designer's solution path (as well as in artificial intelligence). Nevertheless, the cognitive constraints that limit the designer's ability to solve problems, the concepts of "bounded rationality" or "satisficing", are still absent from most of the classical design process methodologies.

### Computer-based implementations

The exploitation of the findings by computer-based systems is slowed down by difficult challenges. Lambell, N. J. et al. (2000) reported the shortcomings they encountered during the implementation of an expert system: An external support system reduces the pace of the thinking process; The designer feels "directed" — what gives him or her the (false?) impression of decreasing his or her creative capacity? Even the visual aspect of the software played a role. The implementation of the findings about the designer's cognitive abilities is irreversibly linked to research in computer-human interactions.

## 5.3. Validity of the experiments

The debate about whether design is a science like physics or not has always been alive. In this particular area, the hypothesis is that the observed phenomena (the cognitive processes during the design activity) are common or accessible to every human being, i.e. under some assumptions, "natural" and "repeatable", thus ensuring the validity of the experiment — in an epistemological perspective. The global scientific approach is thus similar to classical physics: observations of a phenomenon, elaboration of a falsifiable theory, reduction and repetition of the phenomenon in the frame of an experiment, verification of the finding "in real life". This use of a hypotetico-deductive methodology is also the traditional research process in cognitive psychology (Ball, L. J. & Ormerod, T. C., 2000a). Let us take the case of this phenomenon: "early appearance of a core idea". It was brought to light in the seminal work of Darke (1979) by the means of interviews. This has been taken up again by Condoor, S. S. et al. (1992) and Lawson, B. (1997, p. 44-45), and used in Atman, C. J. et al. (1999) to build work hypotheses, and tested in Ball, L. J. et al. (1998), among others. It was finally a part of the support system tested by Lambell, N. J. et al. (2000).

Aside from the epistemological perspective, some questions remain concerning the validity of the experiment.

Reliability (to what extent the study can be repeated) is important for the repetition of the experiment. Most of the papers reviewed gave the number of participants, and the design in brief, but only few revealed the experimental conditions.

Internal validity (to what extent the results reflect reality) is a point of controversy. The "instruments" that transform the verbal protocol into problem-solving process diagram are the researchers responsible for the experiment. Methods have been worked out to thwart the bias. The usual way of analyzing is that two researchers do the job separately and compare their results (e.g. Atman, C. J. et al., 1999). Purcell, T. et al. (1996) propose a four-stage analysis: the two coders apply the coding scheme twice, compare the results, then compare each other's results and finally work together for a final arbitration between the results. Recently, Shah, J. J. et al. (2003) have been developing a system of comparison between the analyses of researchers in design engineering and psychologists. Engineers analyzed designs of high complexity while psychologists analyzed "simpler" ones. The purpose of the study: ideation, remaining the same (the experiment is based on sketch analysis). It turned out that they matched. This has the advantage of decreasing the time of analysis, and this confirms the internal validity of the experiment.

External validity concerns the extent to which the results can be generalized. This subject has not been tackled very often. Only a few studies were found that sought some similarities between the different engineering fields (Goel, V. & Pirolli, P., 1992; Lloyd, P. & Scott, P., 1994). Surprisingly, very few studies discuss the problem of the number of experiments that would give external validity to the study. Indeed the number of subjects studied varies from 1 to 52 experiments from paper to paper. The comparison between the experiments of different laboratories is difficult due to the "scattered and independent nature" of the studies (Cross, N. et al., 1996b). Cross, N. et al. (1996a) developed a workshop where researchers from different universities worked on the same experiments, which allowed better bases for comparison. The reason for the small number of experiments seems to be the fact that the works are still explorative in nature (see e.g. Ball, L. J., 1998), and that analysis is a very time-consuming task. Some sociologists give a justification for a small number of studies: Eisenhardt, K. M. (1989) writes about case-based studies that they are chosen for theoretical, not statistical reasons. Then, if the choice of the sample is correctly made (polar cases like experts and novices are really interesting for this purpose), the results should be valid. However, this justification needs a preliminary acceptance of the paradigm it belongs to (here: postpositivism). This subject needs further exploration.

## 5.4. Placing the findings in context

The experiments on the design activity are studies of a phenomenon that has been isolated from other parameters, among others sociological ones, in order to better understand it. The survey revealed that observation studies and verification of the phenomenon are proportionally fewer than the experiments. This can be due to the fact that this field of study is still in its infancy. Nevertheless, if the cognitive characteristics of the design process have to be exploited, they have to be placed in their context, and confronted with the other phenomena influencing the design activity, especially social factors. Their interrelations might be complex.

*Ethnography* is one of the methods: "it problematicizes the ways that individuals and groups constitute and interpret organization and society on a daily interactional basis" (Schwartzman, H. B., 1993). Ball, L. J. & Ormerod, T. C. (2000b), for example, adapted it and used it — focusing on designers' interactions with their environment, and no longer exclusively on their cognitive activities prior to the study itself, to learn how the design process takes place.

## 5.5. Extension: origins of knowledge

Research studies have given many insights into how experts design, which are their strengths. They have been compared to students, and more and more studies are deciphering the differences (e.g. Kavakli, M. & Gero, J. S., 2001; 2002). Teaching the way experts design: this goal is really important for education. However, analyses of cognitive processes yield information on how the designer works, but not on how he acquired these skills. Thus, complementary to these analyses, retrospective interviews may be needed to get to know where the solutions came from and in what proportions: education, experience, earlier designs, etc. In this way, the experts' skills could be better encircled, and then taught to novices. Finally, designers' reflections on their task could teach us more about the strategic and tactical level of a design activity than VPA does.

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# Paper B

## A Descriptive Model of the Design engineer's Problem Solving Activity During the Later Phases of the Design Process

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# A Descriptive Model of the Designer's Problem-Solving Activity During the Later Phases of the Mechanical Engineering Design Process

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## Abstract

*Many specific and precise methods that support the mechanical engineering designer's work during the conceptual design phase exist, while only a few general methods address the embodiment design and detail design phases. Our study presents the pattern of the designer's problem-solving activity during the later phases of the design process. This model is intended to serve as a basis for further development of tools and methods directly oriented towards the designer at work in these stages of the design process. The descriptive model presented here is developed through observations of six designers at work in controlled experiments, and follows a previous study published elsewhere.*

## 1. Introduction

Numerous methods, based on a theoretical approach or on best practices, are dedicated to the process of mechanical engineering design, or design for short. These methods aim at optimizing the designer's activity of creating and developing an artifact in terms of costs, quality and time, by supporting his or her design activity. The pattern that underlies these methods is that their rigorous and rational application should naturally lead to a satisfying solution. The paradox is that little is actually known about the designer who carries out and is central to all of these methods. The designer is often considered as rational, skilled and with a huge amount of knowledge, but is this assumption relevant for the development of methods that support the design activity?

A growing number of research studies have been dedicated to how the designer actually thinks and acts. Based on findings in the field of cognitive sciences, these works have been mapping the range of skills and limitations a designer possesses with the aim of improving design methodologies. A whole body of knowledge is emerging, and several special issues of engineering design journals (like *Design Studies* vol. 18(4), vol. 19(4), vol. 20(5), vol. 21(5), *Automation in Construction* vol. 7(2/3)) and conferences (Design Thinking Research Symposia, Creativity and Cognition, International Conference on Design Computing and Cognition) testify to the importance of this issue. However, most of the studies reported concern the conceptual phase of the design process. Creativity is indeed central at this stage, and the "outputs" of this activity constitute the less "controlled" part of the design process. Moreover, the decisions taken at this phase are decisive for the pursuit of the product development project.

However, the embodiment design and detail design phases are still important due to the time they consume, the costs they generate and their importance for the quality of the product-to-be. Moreover, even if the working principle of the product is known and the design problem thus well defined, creativity is still required especially during the synthesization parts of these phases, when the product architecture, and the embodiment, "form" and shape of the product still do not exist. A deeper understanding of the designer's activities in the later phases of the design process is therefore needed.

The purpose of this paper is to present a descriptive model of the designer's problem solving activity during the embodiment design and detail design phases, through observation of the basic cognitive tasks fulfilled by the designer. This follows a preliminary study published elsewhere [1]. This paper also presents a refinement of the set of categories used for the analysis of the problem-solving process.

The first part of this contribution presents the background: purpose and framework of the study. The second part will discuss the theoretical limitations that the modeling of the design activity as a problem-solving process implies. The main findings on the cognitive aspects of problem solving in design are also presented. The third and fourth parts will reiterate the methodology used for this study, present the set of categories developed and used for the analysis of the problem-solving process, and the preliminary results of [1]. The descriptive model of the designer's problem-solving activity is then presented and discussed. Finally, future efforts needed to complete this investigation are proposed.

## 2. Purpose and framework of the study

A huge amount of methods have been developed to support the early phases of the design process, which are often precise and rigorous. They do not only 1) allow the designer to structure and plan his or her work, 2) they also consider the designer's limitations by supporting him or her to avoid becoming lost in the huge amount of information which has to be handled, they enhance the designer's creativity, help the designer to prioritize the design activities, etc. 3) They also take into account that teamwork in the design process is a requirement.

On the other hand, design process methods only partly take into account all of these three characteristics when they deal with the later phases of the design process. The process of design (considering the characteristics mentioned above) during the embodiment design and detail design phases is sometimes considered as a less complex activity than the conceptual design phase — in the sense that the task is more well defined — and thus only roughly developed (see e.g. [2], p. 16). Others, like [3] (p. 201) and [4] (p. 136), present a more detailed procedure, which rather concerns the planning of the different design activities for the whole technical system, thus fulfilling the first characteristic presented above, than helps the designer in his or her daily activity. [5] (p. 185-186) claims that it is impossible to have a more "step-by-step process", at least in the early part of the embodiment design phase. In [6], there is no constraining procedure; the author allows the designer the freedom to even switch between the conceptual design and the other phases according to the designer's needs and priorities. Thus the design process is supported partly by the designer's experience. [4] presents a "structure of possible activities in the design process" (p. 135). This structure is supposed to be the same for all the phases of the design process (conceptual design, embodiment design and detail design). If it gives an insight into the activities that the designer may need to perform, there are few guidelines on how to structure these activities.

Thus, during the embodiment design and detail design phases, the designer develops and structures the work, and chooses the techniques, tools and standards needed, based almost exclusively on the designer's experience and education. There is a need to develop methodic support to the designer that structures the design activities during the embodiment design and detail design phases.

To that end, a study has been undertaken whose approach is to observe the designer at work. This should lead, helped by the literature on design practice [7], to identifying the moments where the designer needs support and how this task can be organized. The designer's observations should lead, in turn, to the identification of "best practices" that can be exploited for the development of support. The designer is observed within a four-level framework, partly similar to the structural design process presented by Hubka in [4]: 1) the designer placed in his or her daily work environment; 2) the tactics and strategies applied during the whole embodiment and detail design activities (developed in [8]); 3) the operational, cognitive activities during design, especially problem solving (detailed here); 4) the basic cognitive elements: induction, deduction, abstraction, perception, pattern recognition, attention, intelligence, etc. (these elements are not design-specific, and thus are beyond the scope of the study reported here). Figure 1 presents the framework.

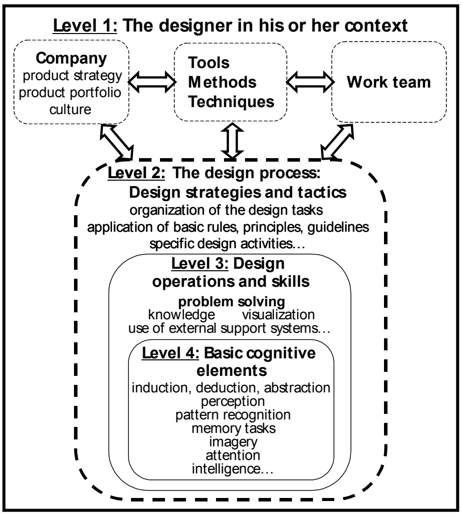

**Figure 1. The Four-Level Study Model of the Designer's Activities.**

In this paper, a refinement of the description of the problem-solving process during the embodiment design and detail design phases is presented. This means that the coding scheme necessary for the study of the designer that had been developed in [1] has been refined (see section 4); further aspects of the problem-solving process not undertaken in [1] are developed, namely, the search for information, the refinement of the problem and the evaluation moments.

## 3. Problem-solving process in engineering design

A design task is often considered as a problem to solve, and problem solving is often modeled as sequential. These views are used as work hypotheses of this study. Their limitations are given in the first part of this section. The second part presents the main findings on the cognitive aspects of problem solving in design

### *3.1. Work hypotheses*

Our work on the problem-solving process is based on two hypotheses that are discussed in this section: that the problem-solving process is sequential, and that most design activities can be modeled as a problem-solving process.

First of all, the concept of "problem" needs to be clarified. Although there are as many definitions of a problem as there are authors, there is a consensus that a problem is a discrepancy between an observed state and a desired state, with no known solution (the observed state and desired state can vary with time). The problem-solving process is then the elaboration of a solution whose implementation suppresses the discrepancy.

The traditional view in the problem-solving literature is that of the "phase theorem", which means that a problem is solved rather sequentially. This idea was first developed by Dewey in 1910 [9], who proposed a five-step model: 1) a felt difficulty, 2) its location and definition, 2) suggestion of possible solutions, 4) development by reasoning of the bearing of the suggestion, 5) further observation and experiment leading to its acceptance or rejection. In the field of mechanical engineering design, as well as in any other field, the problem-solving processes are described in this way (see e.g. [4], [3] and [2]). As described in [10], "the descriptive facet of the [phase] theorem suggests that problem solvers follow a certain sequence of phases. Its prescriptive facet suggests that problem solvers are more likely to succeed if they follow a certain sequence of phases." (p. 48). However, though widely accepted, *the validity of both the prescriptive and descriptive models is still questioned* [10]. No study has so far been conclusive, and we do not even know if the problem-solving processes models in the literature represent the actual process-solving process or if they are "implicit schemata of how problems are, and should be, solved" [10] (p. 48).

The second hypothesis is that most activities in design can be modeled as a problem-solving process. This is a well and widely accepted assumption. Even Simon in [11] presents the problem-solving model: "intelligence", "*design*", and "choice" (which can roughly correspond to: "problem understanding", "solution generation, "evaluation-decision"), using the word *design* to describe the core of the problem-solving process. However, the assumption that the design activity is a problem-solving process has been recently challenged in [12]. Design is rather seen as containing problem solving, rather than being a special case of problem solving; the design problems should be seen as *projects* to handle with an infinite number of problems, rather than just problems. Design thus needs to be seen from another perspective. The rationale behind this claim is developed in [12]. The implications are that the modeling of a design activity as a problem-solving process may not be sufficient to describe it.

During the later phases of the design process, the design tasks are fortunately more well defined than in the conceptual design phase. Thus the last point has limited consequences for the study. The claim developed in [12] should nevertheless be investigated in further studies.

The validity of the sequentiality of the problem-solving activity is still discussed, but this model nevertheless has the advantage of being a powerful tool to describe problem-solving process observations. Thus we chose to rely on it.

### *3.2. Cognitive aspects of problem solving*

The main findings from the literature, valid for both earlier and later phases of the design process, have been presented in a literature survey [7]. Here follows a summary of the main characteristics of human problem solving in design: early appearance and persistence of a kernel idea; design fixation (inclination to stick with early satisficing solutions); lack of flexibility in designer's thinking behavior; superficial assessment; subjective judgment.

## 4. Method of investigation

### *4.1. Observations under controlled experiments*

The most widely used method to observe problem-solving activities in cognitive sciences is to perform laboratory-like experiments with verbal protocol analysis (VPA). Experiments allow a control over many parameters: here we wanted to focus solely on the design process, without external influence (see Figure 1), thus experimentation was the best way to

**Table 1. Categories of the Coding Scheme.**

| Category | Description |
|---|---|
| Irp | Concerns the time segments where the subject asks the experimenter for complementary information on the problem itself. That is, the subject asks for information helping in the understanding of the problem, not for directly developing a solution. |
| Sp | Concerns the time segments where the designer reformulates, re-frames the problem (from [16] and [14]). |
| Ep | Concerns the time segments where the subject evaluates the problem itself. |
| Irm | Concerns the time segments where the subject asks the experimenter for complementary information on mechanics. That concerns formulas, models… |
| Sm | Concerns the time segments where the subject describes the solution in mechanical terms (force, moment; strain, stress; buckling; etc.) |
| Em | Concerns the time segments where the subject evaluates his or her mechanical model. |
| Irs | Concerns the time segments where the subject asks the experimenter for information that directly helps the synthesis activity. It can be catalogues of components, of joints… |
| Ss | Concerns the time segments where the subject creates the form and layout of the support. |
| Es | Concerns the time segments where the subject evaluates his or her solution (layout, form, or the overall solution). |
| Ird | Concerns the time segments where the subject asks the experimenter for information that helps in dimensioning. |
| Sd | Concerns the time segments where the subject dimensions the artifact. |
| Ed | Concerns the time segments where the subject evaluates the results of dimensioning. |
| D | Concerns the time segments where the subject documents his or her work by a detail drawing. |
| Eego | Concerns the time segments where the subject evaluates himself or herself. |
| O | Concerns the time segments where the subject organizes his or her way of working. |

control the information the designer had access to. Verbal protocol analysis is a technique developed by [15]: The subject is recorded while "thinking aloud", and his or her "thoughts" are then transcribed and analyzed with the help of a set of categories each describing a single action. Even if it is still a subject of controversy, "thinking aloud" (the subject says what he or she is thinking) has been the best technique so far in order to obtain a detailed description of a cerebral activity.

In this paper, we used the six experiments designed in [1]. The subjects were three students and three experts. Two students were seniors, one was a junior. All the experts had more than 20 years experience. One has always worked in industry, one always in academia, while the third had worked half in industry, half in academia.

The experimental procedure is given for information in the Appendix. The set of categories used to analyze the transcribed verbal protocol, also called coding scheme, is the development of the coding scheme developed in [1]. The coding scheme is provided in the next section.

### *4.2. Developed coding scheme*

The coding scheme is presented in Table 1.

The model-coding scheme presented 7 categories [1]. It gave insights into the problem-solving activities performed by the subjects, especially solution development (see next section). For this paper, the activities that are addressed are the problem understanding activity, the search of information and particularly the evaluation moments. Thus the coding scheme has been extended to 15 categories.

The evaluation categories (Ep, Em, Es, Ed) were further analyzed following two dimensions: the type of evaluation, and the role of evaluation. The type of evaluation represents the way the evaluation is made: with or without criteria. When the evaluation was without criteria, then the type of evaluation was further divided between a qualitative type of evaluation (good, bad…) or binary type of evaluation (wrong/right). The role of evaluation addresses the aims of these evaluations: decision, reinforcement (or confirmation) of a decision, judgment, comparison between two sub-solutions, and control (or check).

**Table 2. Dimensions of the evaluation moments.**

| Category | Description |
|---|---|
| Types of the evaluation | |
| qu – qualitative evaluation | Concerns the evaluation moment where the designer qualitatively evaluates his or her solution (or the problem). Examples: “This looks strange”, “my part is really clumsy”, “I think I am satisfied with this design”… |
| r – right/wrong | Concerns the evaluation moment where the designer makes a “right or wrong” evaluation, without any criteria (note that this kind of evaluation is not always followed by a decision.) |
| cr – criterion | Concerns the evaluation moment where the designer makes an evaluation with the help of a criterion. |
| Roles of the evaluation | |
| d - decision | Concerns the evaluation moment where the evaluation leads to a decision to continue the development of a solution or not. The evaluation moment and the decision could rarely be separated, the decision being taken implicitly. |
| r - reinforcement | Concerns the evaluation moment where the evaluation is a reinforcement of a previous decision. |
| j – judgment | Concerns the evaluation moment where the evaluation is a judgment of a solution without any subsequent t decision. |
| comp – comparison of solutions | Concerns the evaluation moment where there is a comparison between two sub-solutions. |
| c – check (control) | Concerns the evaluation moment where there is a control or check over what has been done so far. It is different from the reinforcement in the sense that the control episode does not concern a decision, but rather the design activity and its result(s). |

These dimensions are presented in Table 2. The category Eego, representing the moments where the designers evaluated themselves, was not the object of further investigation. This category is included in the coding scheme because this action has been observed in the majority of the experiments (5 out of 6).

The verbal protocol of the experiments has been segmented in elementary problem-solving episodes to which a category of the coding scheme was assigned. This analysis served as basis for the interpretation of the experiments. The results of the previous study relevant for this paper are summarized in the next section, while the results of this study are developed in section 6.

## 5. Previous results: general problem-solving strategy and solution development

As mentioned before, we accepted as our point of departure the general phase theorem. The different problem-solving models present in the literature are not very distinct from each other [10]. Thus we adopted the model developed by Simon [11], which corresponds to the three core steps of the model introduced in our field by Hubka [13], and which is further developed by Eder [14].

The model proposed, then, has the form “task understanding / solution generation / evaluation”. Our assumption was that generating a manifold of solutions was mainly a necessity for the conceptual design phase. This model emphasizes novelty and creativity during the process, which might be not necessary during the embodiment design and detail design phases. Thus we focus mainly on solution generation.

Our first study [1] partly confirmed our assumption. All the designers observed presented the same pattern of a general problem-solving strategy: they quickly understood the problem, developed no more than 2 alternatives, rapidly selected one of them and then lengthily studied and developed this alternative (by dimensioning or not — two students did not dimension, two experts dimensioned with only the help of their experience). The generation (or development) of the solution was interplay between synthesis and mechanic modeling. Synthesis, in short, was the activity of creating the solution, while mechanical modeling was the modeling of this solution. Synthesis usually preceded mechanical modeling. Finally, the detail-drawing episode, the first moment where the designers were confronted with real proportions and measures, was always the case of coming back to synthesis.

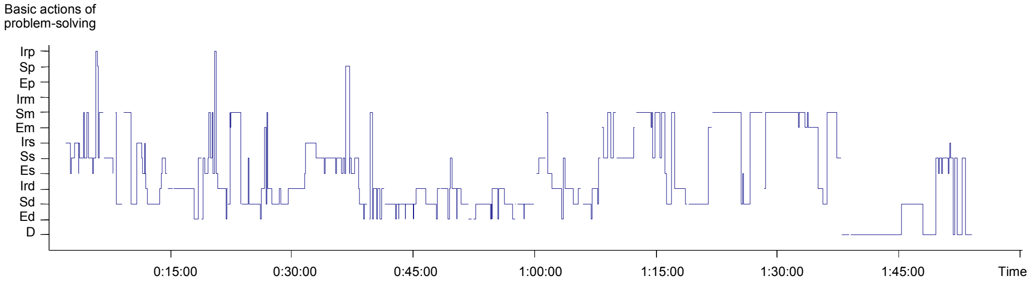

**Figure 2. Problem-solving activity of an expert.**

## 6. Results and Discussion

In this section, we present and discuss the main findings concerning the episodes of information search, problem understanding and evaluation, before we present a descriptive model of the problem-solving process during the embodiment and detail design phases developed from this exploratory study.

The pattern of activities of one expert is given as an illustration in Figure 2. The episodes of self-evaluation Eego and organization O have been removed from the diagram in order to facilitate its reading, and because these episodes were not directly constitutive of the problem-solving process.

### 6.1. Information search

Contrary to our previous study, we distinguished between the aims of the information search. For all but two designers (one expert and one student), the time dedicated to information search on the problem (Irp) did not exceed 30 sec. This is really a short time, and it shows that designers do not question the problem, as they would do for conceptual design [17]. From the expert, as could be expected, no time was dedicated to the search for information that would help the development of a mechanical representation of the solution (Irm). Two students needed that information, one junior and one senior, but the senior needed a model for buckling, which is quite specific. In fact, the solutions designed by the experts were relatively easier to model, thus requiring less information (and less time) [1]. There was not much difference between the designers studied concerning information search for the synthesis activity (the two experts that dimensioned without performing any calculation took less time, however). The search for information concerned the search for standard components. The students took more time studying the standard mountings of the hydraulic cylinder, while they did not bother very much looking for standard components for their design. Finally, the time dedicated to search information for dimensioning cannot be compared: some designers did not dimension at all, while others dimensioned with the help of their experience. The Ird episodes were often more structured than others. Although it is not visible in our coding scheme, we have observed that the designers sometimes used criteria in order to search this information, searched among a large amount of information and then rigorously selected the information with the help of the criteria. Generally, it has been observed that the more well defined the problem is, the more rigorous are the designers in their tasks.

In summary, although designers spent a long time searching information (from 15% to 35% of their time), this information was oriented towards the information they needed and not towards a better understanding of the problem.

### 6.2. Problem understanding

As mentioned earlier, information search for problem understanding is negligible. The time spent for reframing or reformulating the problem is not much either: around 30 sec. to 1 min. (less than 2% of the experiment time). Some designers did not question the problem at all. The designers did not go beyond the brief they received. One could argue that this behavior is due to the experimental, even “scholarly” context of the task (one to two hours in front of an experimenter). But in [17], experts, under the same conditions, had to fulfill a conceptual design task; most of them asked more than needed in order to get an overall idea of the task and not to forget important points. The importance of the problem clarification is emphasized by the literature (see e.g. [3], [14], [17]). Thus this is a point that should be recommended to the designer even at a later stage of the design process.

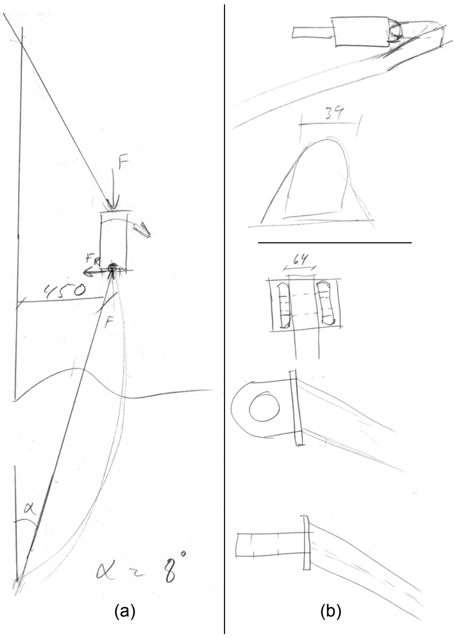

**Figure 3. (a) First sketch of a student; (b) Concretization of the solution: interface problem.**

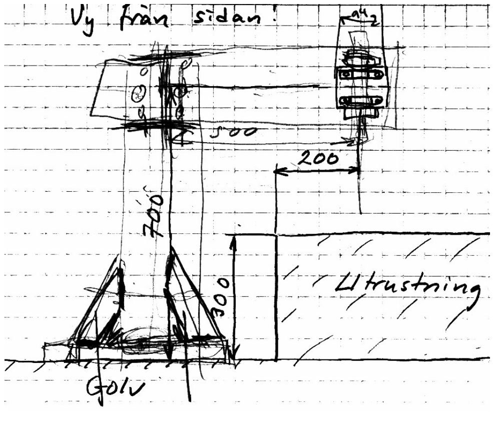

**Figure 4. First sketch of an expert.**

To what extent the designers should spend time on this activity remains unclear, however. Should they question the whole problem? What has been observed is that the designers are really focused on the development of the solution. This makes their work very effective. For real problems, the time given to the designer is not as vague as for conceptual design; the results of their work can be quantified and evaluated; thus the designer has to be effective and focused. The question remains to determine in which proportion of the working time the problem must be reformulated, and how it must take place in the overall design process.

The junior student did indeed spend significantly more time on problem reformulation. However, what has been observed is that his behavior was what in [18] is called "adhocism". At many times, the student did not actually try to understand the problem, but rather tried to reformulate it so that it would fit the technical system he had developed and the knowledge he had. This phenomenon must be taken into account for further development of this issue.

## *6.3. Evaluation episodes*

It as been decided, to avoid overly expanding our coding scheme, that the evaluation episodes comprise the evaluation, decision, verification, and check (control) episodes. Recently, in [14], emphasis has been placed on the action of "reflecting over". A control on our coding showed that this step had been partly included in the evaluation episodes, partly in the solution development episodes (Sm, Ss, Sd).

The evaluations of the problem-understanding episodes were very few; most of the experts did not even have one single episode, like the one presented in Figure 2. This is a logical consequence of the small amount of time spent on problem understanding, as developed in the last section. Otherwise, most of the evaluation episodes Ep were qualitative, and their role was that of judgment.

It has been mentioned in [8] that the experts applied the basic rule of *simplicity* developed in [3], but most often only during the first half of the experiment. Then their design became slightly more complex. This explains why there are an increasing number of evaluation episodes following the mechanical modeling moments during the experiments (in about 30% of the cases for the experts). The students had a slightly higher percentage. These evaluation episodes mainly concerned decision-making episodes (d), and they were always without criteria (half were qualitative "qu", half were "r").

The evaluation episodes for synthesis (Es) were the most frequent for every designer, followed immediately by the evaluation episodes for dimensioning (Ed) for the designers who performed calculations for dimensioning. The purpose of these evaluations comprised all the evaluation roles described above (d, j, r, comp, c). *Decision* was the major cause of evaluation, followed by *judgment* of the solution, *comparison* between solutions and sub-solutions and finally *control* (although to a smaller extent than for Em and Ed).

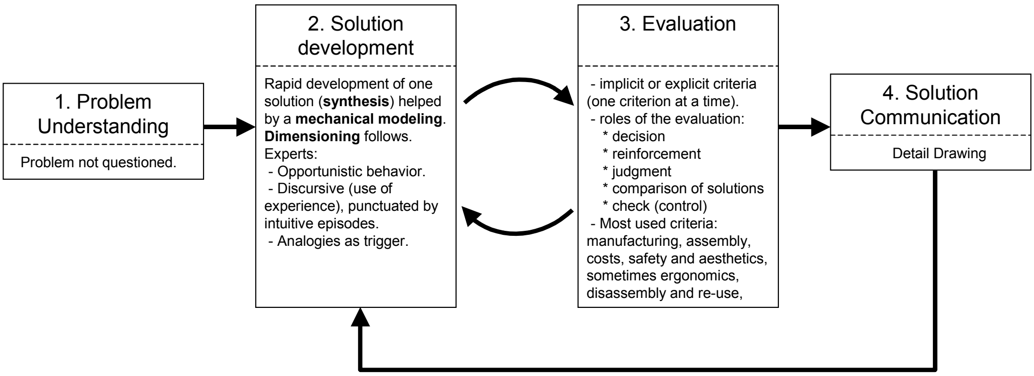

**Figure 5. Descriptive problem-solving activity model.**

Evaluations following dimensioning obviously occurred when the designers explicitly calculated the dimensions. The decision was then, following the result, to go on or come back to the dimensioning. Results of dimensioning were not used to compare two alternatives (at least it did not appear explicitly in the verbal protocol), mainly because the solution alternative was already chosen during the synthesis episode. A minority of decisions was based on criteria. This is due to the fact that the criteria did not need to be given explicitly, the task often being to see whether the component chosen would fulfill the mechanical constraints.

The Eego episodes were relatively rare; they appeared once or twice during most experiments. At this moment, the designer questions his or her own capacity to solve the problem or sub-problem. This moment does not directly concern the problem-solving process, but it showed that the designers are also making a statement about themselves. However, it is difficult to interpret this further. It may be a way of challenging oneself, encouraging oneself to perform better — but it cannot be excluded that this was triggered by the presence of the experimenter.

All the evaluation moments, although representing around 2% to 10% of the experiment time, represented often the majority of the number of episodes (10% to 25%). *Decision* was the main consequence of the evaluation moments (more than the half of the cases), followed by *judgment*. Between 60% and 80% of the evaluations are taken without explicit criteria. Half of them are of type “qu”, half of type “r”. This does not mean, however, that the designers do not have any criteria. It is rather the state of affairs that, in the case “qu” and “r” they use criteria that are intrinsic to their experience [19].

The nature of the criteria used has been described in [8]: the experts mostly take into account manufacturing, assembly, costs, safety and aesthetics, sometimes ergonomics, disassembly and re-use, but most of the factors presented in [3] p. 205 are neglected. The students were not much concerned about factors influencing the design process.

### *6.4. A refined model of the problem-solving process during the embodiment and detail design phases*

As Figure 2 shows, the designer does not follow the steps of problem solving as they are generally prescribed. The designer makes mistakes, needs to sometimes return to problem understanding, has rather an opportunistic way of solving the problem: going very deep into detail when he or she has the knowledge required. And this has been proved to work better concerning the embodiment design for the following reason: by choosing the details of the artifact very early in the process, the designer very quickly apprehends the problem of interfaces between parts [1]. The student, who remains at a higher level of abstraction, needs then to introduce non-standard components, which augments the number of manufacturing and assembly operations (it is worth noticing that the experiment concerned an artifact to be produced in only a few numbers. There may be other conclusions for a mass-produced artifact). This is visible in Figure 3 and Figure 4, which illustrate the differences between an expert and a student.

The particularities of the problem-solving activity have been stressed throughout this paper. However, the generic prescriptive model (problem understanding, generation of solutions, evaluation-decision) still constitutes the core of the problem-solving activity.

What differs is the content of these moments. The *descriptive* model of problem solving during the later phases of the design process is presented below. It synthesizes the details of each phase as presented in [1] and in the preceding section). The model is represented Figure 5.

1) *Problem understanding:* The problem is understood quickly because it is well defined. The designers do not question the stated problem, nor do they come back to it during design.
2) *Solution generation (development):* The designer rapidly develops one solution (synthesis) helped by a mechanical modeling of the solution. Dimensioning follows. Interactions between the mechanical modeling activity and the dimensioning activity have seldom been observed. This process of actions is represented Figure 6. The sequence of transitions between the actions that has been most often observed follows the order i-iv. When material, components and joints are chosen from the beginning, the design process goes more rapidly. The sub-problems are generally treated separately and deeply by the experts. Nevertheless, the first embodiment is generally complete (all the parts that constitute the embodiment are present). The behavior of the expert during synthesis was discursive (use of experience), punctuated by intuitive episodes, in the form of "illumination" in accordance with the model of [20]. Designers used sometimes analogies as triggers. The students used a case-driven analogy (remembered a similar previous case), while the experts used more abstract comparisons, triggering solution ideas (schemata-driven analogy). These observations seem to show that the model of spontaneous analogizing developed in [21] for the conceptual design phase is also relevant for the later design phases.

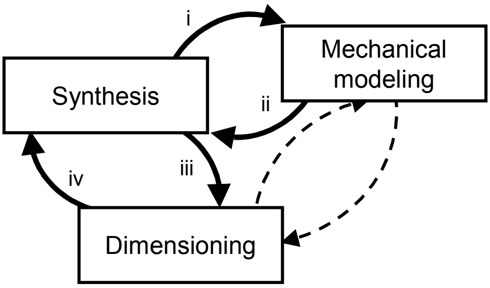

**Figure 6. The process of actions during solution development.**

3) *Evaluation:* Evaluation is made by implicit or explicit criteria. In this case, only one criterion is used. The evaluation moments are numerous, and made at any moment of the design, that is, the designer constantly checks the accuracy of his/her work.
4) *Communication of the solution [14]:* In our case, it is the detail drawing. The detail drawing passively plays the role of control of the solution (because all specifications must be present). All designers face problem with proportions and measures not taken into account during the solution development, and the designers must come back to synthesis.

## 7. Conclusion

We have presented a refined coding scheme that allows the analysis of the problem-solving activity during the embodiment design and detail design phases. This results in a model that describes in detail the problem-solving activity of the designer at this stage.

This model now needs to be complemented by the other levels of study presented in section 2: 1) the designer placed in his or her daily work environment (to be carried out); 2) the tactics and strategies applied during the whole embodiment and detail design activities (developed in [8]). The next step will be the validation of the most important points. With only six experiments, this study was indeed only explorative in nature.

The descriptive model of the design process must then be utilized in order to support the design activity. For that purpose, the sets of actions of the designers need to be interpreted in terms of weaknesses and strengths. The weaknesses should be propped up, while the strengths should be included in a more specific prescriptive model for the embodiment design and detail design phases.

Finally, there is a need to remain aware of different views on the design activity (other than the problem-solving view, like the one presented in [12]) that could give supplementary information on the improvement of the design process.

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## 9. Appendix: The experimental procedure

The experiment, for each of the subjects, lasted for two hours. Each experiment took place in an isolated room. The subject was face-to-face with an experimenter. To the left of the subject, a video camera, manipulated by a second experimenter, recorded the sequence, following the focus and the actions of the subject.

After a short exercise in practicing thinking aloud, the mission statement was delivered to the designer. The subject had to design and dimension a support device for a hydraulic piston that had to be fixed to the ground. The piston, guided laterally, had to resist an axial force of 90 kN. Under the piston, an installation was located on the ground. The support was to be located by the side of this installation (see Figure 7). The specifications of the piston were given in the assignment. This design task, then, was relatively well defined, and should correspond to what can be expected from a similar case in industry. Intentionally, the form-giving aspect was not very complex, so that the subjects had time for both synthesis and dimensioning. The designers were expected to produce a final sketch of the technical system. Finally, there was a short interview in which the subjects were asked to evaluate their design and the experiment.

The assignment has most of the characteristics of an embodiment and detail design task.

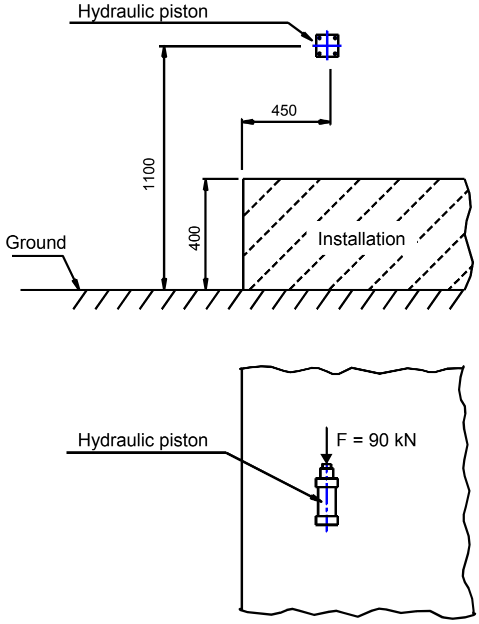

**Figure 7. Sketch of the problem delivered with the assignment [1].**

# Paper C

# A Study of the Mechanical Design Engineer's Strategies and Tactics During the Later Phases of the Engineering Design Process

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# A STUDY OF THE MECHANICAL DESIGNER'S STRATEGIES AND TACTICS DURING THE LATER PHASES OF THE ENGINEERING DESIGN PROCESS

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## ABSTRACT

This paper presents the results of an explorative study on the strategies and tactics applied by the mechanical designer during the later phases of the design process. The method chosen for this study is experiment-based, which is appropriate for an in-depth examination of the designer's activities. Six experiments have been run based on three dimensions: 1) the carrying out of basic design tasks consisting of the designer's strategies and tactics; 2) use of rules, principles and guidelines; and 3) consideration of additional factors. The analysis of the experiments is based on the verbal protocol analysis method.

Although the designers individually showed different approaches, the strategies adopted by the experts presented a similar pattern. Some powerful tactics but also some weaknesses have been identified: the experts reasoned very early in the process in terms of concrete parts and components and thus rapidly solved interface problems; on the other hand, the evaluation and check activities were often considered as secondary.

*Keywords: design process, embodiment design, detail design, designer's behavior, verbal protocol analysis.*

## 1. INTRODUCTION

The later phases of the mechanical engineering design process (called hereafter design process for short) traditionally consist of the embodiment design phase (or system-level design phase) followed by the detail design phase. They cover all the design activities following the conceptual design phase: architecture and embodiment of the product; development of the different product chunks and parts; prototyping; adaptation to production; final specifications; documentation. Numerous tools and techniques — most often computer-based — have been developed that have made the realization of these actual design activities more and more time and cost effective. On the other hand, few changes have been made concerning the design process itself. Most of the existing methods are often structured around the "concretization" of the product during the design process: an iterative refinement and improvement of the features of the product until production launch. Thus the designer's way of working has to be adapted to the different degrees of concretization of the product. Other methods present a set of more general design activities, but leave the designer to structure his or her own work.

Our hypothesis is that the design process can be refined with a *designer-centered* approach. Many methods concerning the conceptual design phase already take into account the designer's skills, competencies and limitations as a human being. For the generation and development of concepts, many methods, based on creative problem-solving techniques, collaborative work, etc. are integrated into design methodologies. The need for extensive creativity and the degree of freedom during the later phases of the design process might be somewhat reduced — constrained by the product specifications — but still, it is obvious that there is a manifold of possibilities for further developing a concept, and this relies largely, if not exclusively, on the designer.

Our overall goal, of which this paper is a part, is to contribute to the development, improvement and refinement of the later phases of the process design by adopting a designer-centered perspective. This should eventually lead to a better design process, ensuring in turn more time and cost effective activities and hopefully a better product quality. This presupposes, however, knowledge of the designer's activities, strategies and the tactics he or she is really applying during the design process. While the designer's activities in the field are extensively documented regarding the conceptual design phase, data are missing when dealing with the design phases that follow. Thus our approach, *de facto* empirical, consists first and foremost in a descriptive study of the designer at work.

This paper presents the second study of a three-stage investigation of the designer's activities. These stages are: 1) the problem-solving activities which represent the operational level of the design activity — this first part has been presented elsewhere [1]; 2) the strategies and tactics applied during the design activity of embodiment design and detail design (presented here); and 3) the designer placed in his or her work environment (to be carried out).

This article is structured as follows. The first section presents the background of the study: a survey of previous research that focuses on the late design phases of the design process and the level-based model of the designer's activities. The second section describes the method chosen for the present study. Finally, the results are presented and discussed.

## 2. BACKGROUND

### 2.1. Embodiment design and detail design phases in general

The methods that describe the later phases of the design process are largely based on the product concretization process. Nevertheless, these methods often present elements that are oriented towards the designer's knowledge and skills. These elements serve as a basis for our study.

One of the most detailed processes of the later design phases is the one described in Pahl & Beitz [2]. They organized the embodiment design phase in 15 steps and the detail design phase in 5 steps. This logically encourages the practitioner to begin with the most important parts of the product ("the main function carriers") and to iteratively refine and improve the layouts and form designs until the final designs are produced. The detail design phase deals partly with the finalization of the details of the product, controlling of standards, etc. and partly with the integration of all the documentation for production and archiving. In order to help the designer, a checklist is added to the process. The designer is encouraged to check systematically for a number of factors that have to be taken into consideration during the process. Accumulated experience and practice have led to the application of some basic rules, such as *simplicity*, *clarity* and *safety*. Pahl & Beitz emphasize their use at any step of the embodiment design and detail design phases. Moreover, the design process works together with a certain number of principles and guidelines that help the designer in dealing with specific aspects and related problems of the design activity. Finally, there is one step in the process presented by Pahl & Beitz that concerns the designer rather than the product: the "check for errors" step, where the designer is encouraged to check for possible design faults.

The theory of technical systems is central to Hubka's work (see [3]). The procedural model of the design process is structured around the concretization of the technical system (see [4], p. 34). The steps are similar to Pahl & Beitz' process, even if some of their embodiment design tasks are carried out in the detail design phase by Hubka (e.g. establishment of tolerances and surface properties). The structural model of the design process ([5], p. 135) is the hierarchical decomposition of the design activities. Below the level of three main design phases (conceptual design, embodiment design and detail design), the design activities are arranged in four levels, with respect to their complexity. Each activity of a lower level contributes to a higher-level activity. The second level, design operations, gathers all activities dedicated to the realization of the technical system, irrespective of the design phase. The third level contains the problem-solving process activities, and the fourth and fifth levels contain activities and actions that are independent of the design activity (e.g. "experiment" or "sketch"). There are not, however, any structure or priorities in the progress of the activities within each level. Finally, a chapter is dedicated to the designer in Hubka [5], but more as a description of what a designer *should* be, rather than about the designer's actions and their consequences for the design process.

In Ulrich & Eppinger's [6] product development process, the later phases of the design process are denoted as system-level design and detail design. The former focuses on the product architecture, while the later actually deals with the embodiment and the detailing of the product part. The system-level design process guides a designer through the particular problem of product architecture. The process of the detail design phase is partly presented.

Pugh, in *Total Design* [7], regroups the later design phases into one single phase, detail design. Unlike the other approaches, the process is not decomposed into a sequence of activities. Indeed, there is not even an imposed frontier between the conceptual design phase and the detail design phase. The designer may need to "jump" from one phase to another depending on his or her needs. Thus, a step is made towards the exploitation of the designer's skills and knowledge. The designer's degree of freedom is also emphasized. Instead of a process, two checklists are given, concerning general points and component design specification elements. This is completed, as in Pahl & Beitz [2] with a selection of principles and guidelines. The *simplicity* rule is also well emphasized here.

Like Pugh, Ullman in *The Mechanical Design Process* [8] regroups the later design phases into the "product design" phase. The model of this phase is structural like Hubka's model, with activities that are not sequenced. Even more, it is asserted that most of these activities are simultaneous.

### 2.2. Studies of the designers' tactics and strategies

Studies of design activity in the later phases of the design process are relatively sparse in the literature. Indeed, most of the studies concern the observation of the conceptual design phase. This may be due to the fact that at the conceptual level the problems presented to the designers are ill defined and susceptible to adding considerable biases to the process of finding a solution. This is also due to the intensive need of creativity and the effort made to understand it. Finally, the decisions taken at this phase are crucial to the further development of a product, although the later phases of a product design are still important concerning the time they take, the consequences they have on the subsequent production of the product, and the extensive costs they involve. Because of the nature of the different phases of the design process, the findings of the studies of the conceptual design stage can hardly be extrapolated to embodiment design and detail design.

In a previous literature survey, described in Motte & Bjärnemo [9], a set of sixty papers and books concerning the cognitive activities of (conceptual) design were selected. This set has been used once again to find studies related to the goal of this paper. In addition, the last conference proceedings of ICED and DTM (ICED'01, ICED'03, DTM'03) have been screened. The studies that addressed the goal of this paper are presented below.

Based on past studies of mechanical designers, Ullman [10] stressed the importance of sketching. He showed that if the designers often begin with the product architecture and then add details about “shape and fit” (2002, p. 57), these three aspects are strongly correlated. Moreover, the elements related to the design activity that the designers handle most — at a tactical and strategic level — are 1) manufacturing and assembly, and materials; 2) costs; and 3) requirements.

The study by Lewis *et al.* [11] covered both the conceptual design phase and the embodiment design phase. Experts and students were asked to solve the same task and enter their process in a logbook. All three professional designers reported that they had used their own method, developed over the years. What they described may roughly reflect what they did, but Visser [12], in an earlier study, showed that the plans the designers described are generally not applied in integrality. They serve as “triggers of action”, as guidelines, but “as soon as other actions are more interesting, [the designer] abandons his plan to proceed with these actions” (1990, p. 247). Visser’s method was observation with simultaneous verbalization. The important point of that study is that a clear design process, followed or not, clarifies the situation and helps the designer through his design process.

Eisentraut and Günther [13] studied four experts whose task was to solve an adaptive design problem: modify the height and inclination adjustment of a writing table. The designer who had the best solution was the only one who documented his process exhaustively. He analyzed his solutions in concrete, but incomplete, sketches, and combined the good ones. In a further paper, Eisentraut [14] showed that the individual problem-solving process the designers developed through education and practice determined the way they organized their design process.

### 2.3. The different levels of study of the designer’s activities

In order to obtain a comprehensive image of the design process as a whole (within the designer-centered perspective), we have developed a model of the designer’s activities based on four levels, from the sociological aspects of the design process to the basic cognitive elements that support it. This model is used as a framework that structures our investigation into the design process. The first level of this framework is based on systemic considerations of the problem: the environment in which the designer works may have a decisive influence on the execution and outputs of the design process activity [15]. The structure and hierarchy of the other levels are similar to the one presented by Hubka [4,5] and constitute a representation of the problem-solving process that can be found in the literature [16]. The four-level study model of the designer’s activities is presented in Fig. 1.

The highest level is that of the designer in his or her work environment. The designer has to consider a given task (a chunk or a part of the whole product) that has to be fulfilled within a given time. The designer interacts with the environment in terms of computer-based software, handbooks, etc. The designer can ask for help from other designers (if available). Part of his or her work may be performed as a team. The designer may be subordinated to decisions made by his or her superior.

At the second level, during the actual designing, the designer deploys a strategy adapted to the design task and applies tactics to solve the problems at hand by organizing the design activities, applying rules, principles and guidelines.

These strategies and tactics might in turn be decomposed into design operations. At that level, cognitive aspects are considered, among others creativity, the problem solving process, knowledge, visualization, and external support systems like sketching and computational tools. While this domain is extensively studied at the conceptual design phase, little work has been done so far concerning the embodiment design and detail design phases. Fricke [17] focuses on task clarification. The study by Ball *et al.* [18] is oriented towards electronic engineering, where problems are slightly different (no constraints on form design, for example). Concerning the problem-solving process activities, it was found that the procedural process “information search – solution finding – evaluation / decision” is followed. However, the designers did not try to generate several solution candidates as in conceptual design, but alternated between synthesis (solution creation and refinement), mechanical modeling of the problem, and evaluation [1].

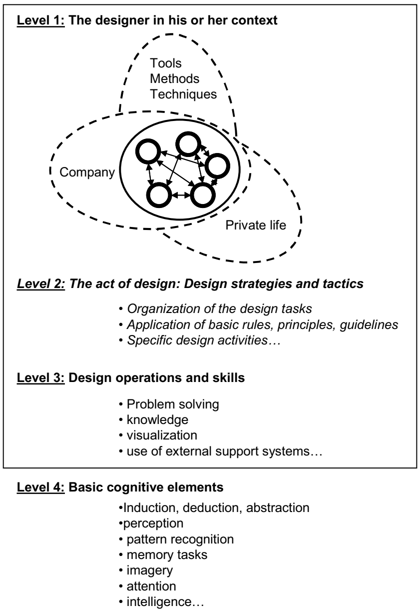

**Figure 1. The four-level study model of the designer’s activities.**

Finally, these design activities are decomposed into basic cognitive elements: perception, pattern recognition, memory tasks, imagery, attention, intelligence, etc. The problem-solving process, for example, is supported by such things as induction, deduction, abduction and abstraction. These basic cognitive elements are still the focus of active research in cognitive sciences; the mechanisms behind the notions of deduction or induction, for example, are still far from established (see Bisanz *et al.* [19] and Rips [20]). Note that these elements are not specific to design activities. Moreover, the evolution of these basic elements is the result of a life-long process and can hardly be taught and changed in a simple and rapid manner. However, studies of the basic elements might reveal additional differences between experts and novices, and they could also partly explain creativity. Studies concerning these basic cognitive activities are, for example, Lin & Wang [21], who studied abduction in an industrial design problem, and Kavakli & Gero [22,23], who analyzed sketching as a mental imagery process.

The level of elementary cognitive elements, which is the concern of the design theory field, is beyond the scope of the study reported here. Our study is limited to the three highest levels, of which this paper addresses the second level.

## 3. METHOD

### 3.1. Verbal Protocol Analysis (VPA)

VPA is a well-suited method for an in-depth study of human-specific tasks and activities. VPA is based on the "think-aloud" technique. The subject is asked, during an experiment that varies from one to four hours, to think aloud, i.e. to describe aloud what he or she is thinking while solving a design problem [24]. The experiment is recorded on videotape, the audio portion of which is later transcribed. The verbal protocol is then analyzed through a coding scheme, which is a set of categories that represent a cognitive activity or a basic design step. The coding scheme is developed based on former ones or, as with the interview technique (e.g. [25]), based on a pre-analysis of the verbal protocol that will iteratively lead to the discovery and organization of the categories. As in ethnography, the experimenter directly observes the design process. As designers are used to working alone at the later phases of the design process, the framework of a controlled experiment has a little influence on the design process itself. The design process is isolated from external factors, and hence the third and the fourth levels of activity are separated.

### 3.2. Description of the experiment procedure

The experiment procedure has been described elsewhere [1] and is only briefly summarized below.

The subjects selected for the experiments were three students and three experts (more than ten years of experience in mechanical design). The three students all came from Lund University, and have all followed the product development–mechanical design syllabus within mechanical engineering.

The experiment, for each of the subjects, lasted for two hours. Each experiment took place in an isolated room. The subject was face-to-face with an experimenter. To the left of the subject, a video camera, manipulated by a second experimenter, recorded the sequence, following the focus and the actions of the subject.

After a short exercise in practicing thinking aloud, the mission statement was delivered to the designer. The subject had to design and dimension a support device for a hydraulic piston that had to be fixed to the ground. The piston, guided laterally, had to resist an axial force of 90 kN. Under the piston, an installation was located on the ground. The support was to be located by the side of this installation (see Fig. 2). The specifications of the piston were given in the assignment. This design task, then, was relatively well defined, and should correspond to what can be expected from a similar case in industry. Intentionally, the form-giving aspect was not very complex, so that the subjects had time for both synthesis and dimensioning. The designers were expected to produce a final sketch of the technical system. Finally, there was a short interview in which the subjects were asked to evaluate their design and the experiment.

The assignment has most of the characteristics of an embodiment and detail design task, in the sense that the designer has "to fulfill a given function with appropriate layout, component shapes and materials" ([2], p. 205). It takes into account most of the factors affecting embodiment design and detail design phases listed in Pahl & Beitz [2] (reported in Table 2). This ensures that the strategies and tactics deployed by the designers have a high probability of generalization. Experiments with a slightly different design task should nevertheless be carried out to confirm this point.

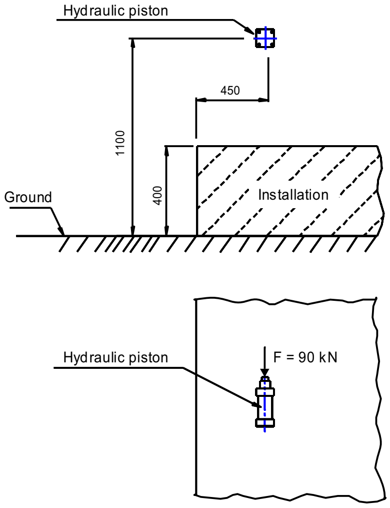

**Figure 2. Sketch of the problem delivered with the assignment [1]**

### 3.3. The elements of the study

From the literature review, three dimensions were considered important for the study of the designer's second-level activities. First, we studied the design process itself by decomposing the actual process into single steps. Then it was checked to see if the designer applied the basic rules (clarity, simplicity and safety), or any other principles or guidelines. Finally, we checked if the designer, during the design process, was aware of other factors concerning the product life cycle (e.g. production, transport, recycling).

*3.3.1. The basic design tasks of the design process*

Initially, a set of categories representing the basic design steps or tasks performed by the designer during the embodiment design and detail design phases was developed. These steps, or more precisely the way they appear and are structured during the experiments, serve as a basis for the analysis of the strategies and tactics applied during design. The categories are presented in Table 1.

**Table 1. Categories of the coding scheme (basic design tasks)**

| *Task Abb.* | *Design Task* | *Definition* |
|---|---|---|
| Id | **Identification of the problem** | Research and identification of the relevant information in order to understand the problem. Understanding of the problem. Identification of the requirements. |
| | **Layout and form design** | Activities that concern the embodiment of the function carriers, the layout of the system, the design of the frame around the function carriers. In our case, there is no frame; the function carriers embodiment is the main task. |
| $L_{ss}$ | Scale of spatial constraints | Define (calculate if necessary) the space needed for the technical system. |
| $L_{sd}$ | Synthesis | Design (embodiment) at an abstract level of the technical system. |
| $L_{cc}$ | Choice of components | Dimensioning and choice of the components (standards or not) of the parts that form the “body” of the technical system. Consideration of the loads. |
| $L_{cm}$ | Choice of material | Choice of the material (steel…). |
| $L_{cj}$ | Choice of joints | Choice and dimensioning of the fixation systems that assemble the components together or with the environment (weld, screw). |
| $L_{compa}$ | Ensure compatibility/interface | Consideration of the compatibility of the different parts. |
| | **Evaluate against technical and economical criteria** | |
| $Ev_c$ | Find criteria | Criteria used to evaluate the design. |
| $Ev_{of}$ | Find objective function | Modeling of the task into a function to optimize. |
| $Ev_t$ | Evaluate against tech. criteria | Special attention dedicated to the technical and economical criteria, which are crucial to embodiment design and detail design (Pahl & Beitz 1996). |
| $Ev_e$ | Evaluate against econ. criteria | |
| | **Check** | |
| $Ch_e$ | Check for errors | Verification of any possible error in the design or the drawing. |
| $Ch_f$ | Check for disturbing factors | Check for possible factors that could influence the usual use of the technical system (from [2]). |
| D | **Detail drawings and documentation** | Activities linked to detail drawing (scale, layout of the drawing, organization of the task, drawing) and documentation (list of bills, manufacturing and assembly instructions…). |

The tasks of the second category, “Layout and form design” have been partly extracted from a pre-analysis of the protocols, and partly from the literature. This is especially valid for the “scale and spatial constraints” task ($L_{ss}$). The “synthesis” task ($L_{sd}$) represents the creation activity of the support device, by combining retrieval and comparison of relevant knowledge (mechanical, technical, etc.) with the current design problem. It is here the putting together of the elements to fulfill the physical requirement from the design problem at hand takes place (see [1]). On a more concrete level, the tasks of choice of materials, components, and joints, appear clearly ($L_{cm}$, $L_{cc}$, $L_{cj}$). The problem of compatibility between the different elements of the technical system also sometimes appears ($L_{compa}$).

*3.3.2. Basic rules, principles and guidelines*

Numerous rules can be found in the literature, but still *clarity*, *simplicity* and *safety* are the fundamentals of all of them [2].

*Simplicity* means that the design must not be complex, is easy to understand and is designed with a minimum of resources. Simplicity implies simple forms and as few components as possible, which leads to lower manufacturing costs, less wear and less maintenance [2,7]. *Clarity* means that the function and the working principle of an element can be better predicted and clearly defined within the design. This implies a clear and logical function structure, control of the inputs-outputs of energy, material and signal, description of the relations between causes and effects of the elements, avoiding eventual side-effects as well as re-analysis and numerous iterations for refining the solution [26]. *Safety* means that the element should secure the technical functions as well as integrity for humans and for the environment.

These basic rules are supported by guidelines based on the constraints of the design, defined during the conceptual design phase. They cover the range of design for X as well as ways of dealing with some physical and natural effects/phenomena like corrosion, wear and thermal expansions.

Finally, these general rules and guidelines are completed by principles, “laws” if you will, focusing on particular design aspects. These have been verified in practice and proven to facilitate the design [27-29,2]. If, for example, “a force or moment is to be transmitted from one location to another, with the minimum possible deformation, then the shortest and most direct force transmission path is the best” [28]2].

*3.3.3. Other factors influencing the design*

During the design of a product, the designer has to think of many other parameters than the mechanical design itself: manufacturing, logistics, packaging, etc. The list of factors presented in Table 2 is adapted from the checklist by Pahl & Beitz ([2], p. 206). The factors in parentheses are those with less important weight for this particular experiment.

**Table 2. The factors influencing the design**

| *Factors* | *Description* |
|---|---|
| **Safety** | Component reliability<br>Functional reliability<br>Operational safety<br>Operator safety<br>Environment safety |
| **(Ergonomics)** | Interaction with users |
| **Manufacturing / Assembly** | Manufacturing of the product<br>Assembly of the product |
| **(Quality control)** | Consideration of quality control during production |
| **Transport** | Transport, packaging |
| **Operation** | Noise, vibration under operational state |
| **Recycling** | Recycling of the product |
| **(Maintenance)** | Easy maintenance of the product |
| **Costs** | Design costs<br>Production costs<br>(Use costs) |
| **(Dismantling)** | Dismantling of the product |
| **(Re-use)** | Re-use of the product |
| **Schedules** | Production launch<br>Delivery of the product |

### 3.4. The protocol analysis process

The verbal protocol was structured as shown in Table 3. Apart from the dimensions described above (design tasks, use of rules, principles and guidelines, and consideration of additional factors), attention was directed to the social behaviors that could bias the designer's problem solving process. The next three columns are the protocol itself, written from the tapes, which concern the verbal exchange between the subject and the first experimenter and the subject's actions and focus. The last column, "others", contains remarks concerning the experiment and possible improvements that were reported during the experiment.

The analysis was executed concurrently by two analysts. The attribution of one category to one episode (one action) was subordinated to the acceptance of this category by both analysts.

## 4. RESULTS AND DISCUSSION

Even under the conditions of a controlled experiment, the data collected are qualitatively very rich. The results: specific activities, the later phases of the design process, the strategies and tactics interpreted from the analysis of the protocols of the students and the experts among the different dimensions are presented in section 4.1. The quality of the results and the experiment is then discussed in section 4.2. Finally a synthesis of the strategies, tactics but also weaknesses of the design processes carried out by the designers are presented in section 4.3.

### 4.1. Analysis of the designers' behavior

The three dimensions (1) design tasks, consisting of the designer's strategies and tactics, 2) use of rules, principles and guidelines, and 3) consideration of additional factors) are successively analyzed. The contrast between experts and students helped to differentiate their respective behaviors. The experts and the students have been arbitrarily denoted as A, B, C and 1, 2, 3 respectively, corresponding to the order in which they carried out the experiment.

#### *4.1.1. Description of the design processes*

With the coding of the experiments, it was possible to represent the design process of the designer through time. The design processes along the three dimensions used for this study are represented in Fig. 3 for expert A. This designer was chosen because his design process is representative of most of the designers studied.

The designers adopted different strategies: expert A and student 2 performed regular mechanical analyses, based on design principles, in order to establish the dimensions of the support, while the other experts established their dimensions purely on the basis of experience. The other two students did not embark upon dimensioning the support during the time of the experiment. Thus the time and energy dedicated to most design tasks varies greatly.

It did not take the designers long to understand the problem (category Id) — between 1½ and 3 minutes, regardless of the time they took to solve the problem. Most of this time was spent at the beginning of the task, but also occurred at different points throughout the task execution (these figures correspond to the accumulated spent time). Neither the students nor the experts asked questions beyond the scope of the actual task. They did not question the relevance of the task, the working environment of the technical system, nor the means of production; they just directly started working on the task assignment.

The solution principle chosen by the designers determined the time used for the second category, "scale of spatial constraints". Amazingly, all the experts designed a support device that had the shape of an arm taking the flexion created by the force (see Fig. 2), while the students preferred a solution that took the force directly, by means of a beam. Thus they needed to place it as near as possible to the equipment below the piston. They had to come back several times to this activity and spent more time: experts A and B needed less than one minute and no iteration while the students needed several minutes and iterations, alternating with evaluation tasks. Designer C needed extra time when she changed her design for safety reasons (see section 4.1.2).

The designers who performed mechanical analysis in order to dimension their technical system had slightly the same pattern of behaviors (in order not to call it a strategy). They defined a rough layout by synthesis, chose the material based on

**Table 3. Protocol table**

| *Time* | *Tasks in embodiment design and detail design* | *Basic Rules Principles Guidelines* | *Other factors considered* | *Social behavior* | *Verbal protocol* | *Motor activities* | *Focus* | *Others* |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |

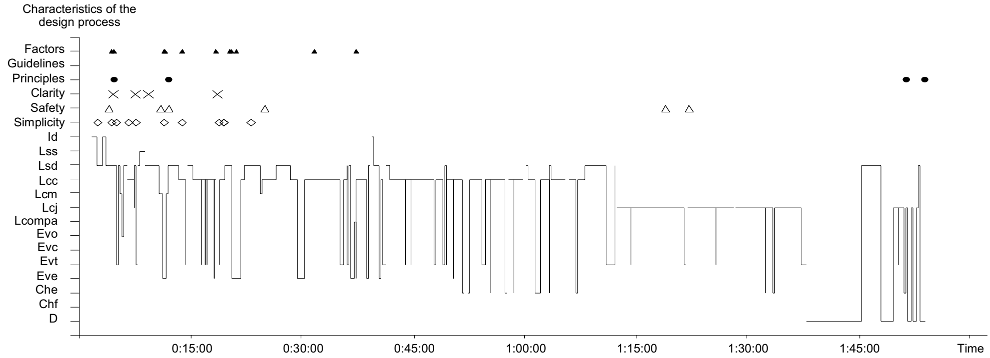

**Figure 3. Basic design tasks performed by expert A**

an economical evaluation (the cheapest), then dimensioned *each* component in an iterate way in order to find the *optimal* one. They were led to evaluate their design more often than the other designers, around one and a half times more, because they "automatically" compared their results to the specifications. *Automatically* here means that the evaluation was passive. They regularly came back to the synthesis task, that is, reasoned in a more abstract way in order to model the sub-problem and refine the shape of the components. Having chosen one concrete component, they dimensioned the following one. The "component choice" category ($L_{cc}$) represented 33% of the experiment time for expert A and 15% for student 2, to which the time for synthesis is to be added (which represents in total around 40% of the work for expert A and 35% for student 2). They then spent some time on the joint choice category ($L_{cj}$) before they began the final drawing.

In comparison to expert A, student 2 needed more time on the synthesis task. This was partly due to a lack of experience: the mechanical analysis methods are known but not fully mastered. But this was also due to the design itself that was more difficult to analyze. The student — in fact, all the students — needed more time to study the component interfaces ($L_{compa}$). They did not look at the interfaces until late in the process. Then, doing so, they developed *ad hoc* solutions that were no longer standard components, instead of re-thinking their initial design. The experts, on the contrary, reasoned very early in terms of components, and during the synthesis task the interaction of the different parts was taken into account.

The designers who did not establish the dimensions analytically followed the same process, but the time dedicated to the choice of components and joints was significantly lower. Expert C spent 6% of her time, that is, less than 4 minutes. Expert B spent 14% but presented two alternatives to the problem. Students 1 and 3 did not choose any components, remaining at a synthesis level.

The evaluation activities were more frequent by designers A and 2 than the others, because of the longer dimensioning process. These activities represented 20% of all the activities (in terms of number of episodes) by designer A, and 24% for designer 1 against 12% for the others. However, the time for each evaluation was really short: between 5 and 24 seconds on average. Indeed the designers did not use any general evaluation function or evaluation criteria more than: "This must be cheap" (categories $E_{vo}$, $E_{vc}$). Expert A and student 1 used it for their dimensioning. This was not evoked by the other designers, even if it was subjacent to the design process of experts B and C. Thus, there was no use of any clearly stated objective function; this tactic was ignored by the subjects studied. The economic evaluation was less often used, between 0% and 28% (designer A) of the evaluation episodes.

The evaluation episodes ($E_{vt}$, $E_{ve}$) served indirectly as measures of design skills. For student 2, the evaluation episode was followed in 40% of the cases by a change of action. That meant for example that the student could not follow the current basic design task begun before evaluation but had to refine his knowledge of the problem or modify his solution principle (25% of the evaluation episodes). Experts, on the contrary, had a change of action in 24% of the evaluation episodes for A, and 10% for B. C had as high as 40% change of action after an evaluation episode, but they occurred at the drawing (D) stage (see below). Moreover, the student had a majority of evaluation episodes during the synthesis phase (50%), followed or not followed by a change of activity. Expert A had in comparison 13% of evaluation episodes during the synthesis phase, the remaining episodes being shared between component choice, material choice and joint choice.

Only experts checked for errors ($Ch_e$): 8% of all the episodes for A, 4% for B. The students, on the other hand, did not verify their design. This situation is probably due to the limited time of the experiment; it shows, however, that the experts check their work earlier in the process. Only expert C looked upon possible disturbing factors (checked for possible factors that could influence the usual use of the technical system – category $Ch_f$). She considered that the piston, although already axially supported, could break under extreme use conditions. She then modified her first, simple, design into one that would function more safely.

The participants were asked to turn in a final sketch with all the information needed for further development. Experts A and B and students 2 and 3 made a scale drawing (category D). *All* designers discovered mistakes in their detail drawings, in particular spatial constraints. This is especially apparent for expert C, who began the scale drawing activity early in the process and went back and forth from synthesis to choice of components in order to fulfill "demands" illustrated in the drawing (which also explains the great number of changes of action after the evaluation episodes following the drawing activities).

### *4.1.2. Basic rules*

The basic rules of simplicity, safety, clarity, were studied parallel to the single design process activities. As in the last section, the rules have been interpreted by the designers' descriptions of their actions.

It is visible in the figures representing the design process for experts A and C and student 2 that the application of the basic rules occurs early in the process, and almost exclusively during the synthesis activity. This is when the designers develop the rough layout of the solution and give form to the parts. Expert C applied these rules at the end of the design process because of the need of refining the support device created by the final drawing activity. The students applied the rules in a somewhat more dispersed way, along with new insights of their designs.

*Simplicity* is, among other things, the use of standard components and simple forms. This has been fairly well understood by the students who began by trying to make their designs simple *at the beginning*. Simplicity is mentioned by both experts and students on average 5 times per hour during the design process. But if there is a need of modification, the way the students proceed is by locally acting on the problem, and without applying the simplicity rule. This often led to the design of unique parts and complication of the overall design. The simplicity rule gave successful solutions on the experts' side. The designs are minimalist, the need for manufacturing operation is very limited, and a majority of components are standardized.

The *safety* rule is used relatively more often by the experts than by the students (evoked on average 5 times per hour). Nevertheless, the students mostly considered component reliability, and sometimes the functional reliability, while 2 experts even considered the operator safety (chamfers to prevent injury during manipulation). Expert C paid attention to the functional safety: she took into account that the hydraulic cylinder could break under use and designed an additional support part to preclude this eventuality.

The *clarity* rule was the rule that the students applied least, and this made the greatest difference between the students and the experts. As a result, students' designs were difficult to analyze, and the force flows were difficult to establish. However, the experts did not apply it systematically either. Both experts A and C felt some difficulties with some particular elements of their design, but their first reaction was to try to analyze the problem in depth instead of searching for clearer solutions. They eventually did so, earlier than the students, but this shows that the rule of clarity, though powerful, is not a natural principle.

### *4.1.3. Principles/Guidelines*

The observation of the activities of the designer and of their designs served as the basis for the analysis of this dimension.

The students more often applied principles and guidelines than the experts. They applied the principle of force transmission (principle of uniform strength and principle of direct and short force transmission path, [2], p 239-241) (a beam transmitted the force applied to the piston directly to the ground), and the principle of stability. Students 1 and 3 applied the principle of self-help: a second beam positioned symmetrically to the first prevented buckling. Nevertheless, if these solutions were clever on an abstract level, their embodiment was considerably more difficult. It resulted in complications in the product layout and form and in the design of the unique parts. The experts were more pragmatic in their approach and tried to apply principles only in concrete cases.

Student 2 was the only subject that used guidelines: one for the dimensioning of a beam with consideration of buckling and one for the calculation of welding joints.

### *4.1.4. Other factors*

The subjects were considered to be taking care of factors other than those directly concerned, when they explicitly referred to them: to choose between bolts or welding joints was an explicit reference to the factor "manufacturing/assembly".

The factors "costs" and "manufacturing/assembly" were the ones most considered. The experts evoked them more often than did the students (8 times versus 4 times on average). Moreover, expert A thought about the possibility of dismantling, while expert B thought about the durability of the product.

Amazingly, no one evoked the problem of transport (most of the designed support devices weighed more than 100 kg), of control, of maintenance or of recycling. This was perhaps of minor importance in the frame of this experiment, but it tends to show that factors other than "costs" and "manufacturing/assembly" are considered secondary by designers and are not yet fully and naturally integrated in the design process.

## **4.2. Quality of the results and of the experiments**

The quality of the results concerns the reliability of the data, the reliability of the interpretation (the results presented in 4.1), and the validity of the results.

The reliability of the data depends on their collection and on the methods that are applied. The VPA method has been widely used in the field of cognitive psychology, and more than a hundred studies in mechanical engineering are based on it. Early experiments have shown that the think-aloud process has the side effect of slowing down the thinking process, but not its efficiency [24]. The data are then recorded on videotape, so there is no loss of data during collection.

The discontinuities that can be observed in the charts (see e.g. Fig. 3) correspond to events that occurred during the experiments and were not related to the design problem. The subject, for example, sometimes began a discussion with one of the experimenters on another subject than the design problem. This was often the first sign of fatigue and was a way of relaxing. On other occasions, the designer felt himself obliged to justify why he or she had made a calculation error. Finally, some episodes could not be coded, because the designer remained silent for some time or was inaudible. These non-coded episodes represent 2%-3% of the total amount of episodes, that is, one or two episodes of each of the experiments. The discontinuities represent between 4.5% and 8.5% of the experiment time; thus they do not interfere with the subjects' overall process of design.

**Table 4. Strategies, tactics and weaknesses**

| *Strategies* | *Tactics* | *Weaknesses* |
|---|---|---|
| General Strategy:<br>Rapid understanding of the problem.<br>Considering, very early in the process, the shape of the parts and their interactions.<br>Concrete choice of materials.<br>Optimized choice of standard components.<br>Dimensioning of the joints.<br>Variations:<br>Dimensioning by experience or by mechanical analysis.<br>Often depth-first strategy.<br>Clear method that is loosely followed. | Think in terms of standard components.<br>Think in terms of concrete shapes.<br>Document the work.<br>Detail drawing.<br>Use of basic rules.<br>Criteria:<br>Minimize costs.<br>Avoid unique parts.<br>Take production into account.<br>Wait until late before using principles and guidelines. | Do not ask beyond the assignment.<br>Do not plan design activity (at an operational level).<br>Do not use a developed objective function.<br>Check activity considered as secondary.<br>Basic rules often followed only at the beginning of the design process.<br>No check for other factors than "costs" and "manufacturing/assembly".<br>Students:<br>Seldom check their design<br>Design knowledge not mastered (lack of experience) |

One of the weaknesses of this method is that the categories that are used for coding the experiments are developed and used for interpretation by the analyst himself. In this study, the coding scheme was submitted to a third person, an expert in mechanical design, who could judge the relevance of the categories. Moreover, in the literature the categories differ between different studies and different authors, which makes it difficult to compare them, but the important point is that they must be able to describe fully and independently the different episodes of the experiments and allow a clear interpretation of the events.

As for ethnographies and case-based studies, these results are not valid in the sense that they cannot be generalized to all designers and students. But the purpose of this study is explorative: describe what continually happens during the later phases of the design process, extract the important actions and behaviors of the designers and deduce the strategies and tactics they apply. These important phenomena can thus be studied more closely, repeated and validated. The designers' activities that will need further development are presented in the next section.

### 4.3. Strategies, tactics and weaknesses

From the analysis of the designers' behavior presented in section 4.1, we made a synthesis of the elements of importance for the study: 1) the designers' strategies; 2) the tactics applied; and 3) the weaknesses of the design process observed. These elements are summarized in Table 4.

The strategies that have been observed in the experts present a similar pattern: a rapid understanding of the problem; a synthesis activity that takes into account, very early in the process, the shape of the parts and their interactions; the concrete choice of materials; the optimized choice of standard components; the dimensioning of the joints. Some designers used their experience to dimension the product instead of carrying out regular mechanical analyses, but the sequence of tasks is the same. The designers did not follow a design process oriented towards the progressive refinement and improvement of the product. They did not distinguish between the embodiment design and detail design phases. Instead, they went far into detail considerations before coming back to the synthesis activity. The help procured by the detail drawing activity (a detail design task) shows the benefit of doing so early in the process. That tends to corroborate our hypothesis that the embodiment design and detail design phases can be improved by focusing on the designer's activities rather than on the product evolution. It has also been observed that the designers have a clear method that they use as a starting point (namely problem understanding, mechanical analysis, synthesis) but then follow it loosely, as can be seen in the designers' charts. This supports Visser [12]'s study.

We found out that this process is very similar to Ullman's [8]'s description of what is occurring in the product design phase. The form, material, components and connections (joints) of a product are indissociable at the beginning of the later phases of the design process on an abstract level of conception. This activity actually corresponds to the synthesis category of the coding scheme.

The experts also used some tactics to get rid of the difficult problems early in the process. They think "solution-wise": they already have in mind the possible shapes for the components to use and try to combine them with respect to force flows. Thus they avoid later problems of spatial constraints and of interface compatibility. Early on, they draw a concrete sketch of the solution on which they can base their analysis. They also have in mind established criteria: minimize the costs; take into account the manufacturing and assembly constraints; and avoid unique parts. The experts tended to document their work more thoroughly, while the student used writing only as an external memory support. Finally, the detail drawing helped everyone to find mistakes.

However, some weaknesses (at least perceived so) have been identified. The designers don't ask questions. They begin designing as soon as they understand the problem. This restrains the problem space, which is effective but can hinder the finding of better solutions. It was, for example, written in our task assignment that the hydraulic piston was axially supported; nobody asked how, nor if it was possible to use this support for the design. The design problems at the later stage of the design process seem to be taken rather as school exercises than as real tasks. Nobody planed his or her work; the designers just tried to go as far as possible in solving the problem. The evaluation and check activities are considered as secondary by the designers. Pahl & Beitz [2]'s steps are important in this context. By including them into the design, they show how the checks and evaluations are central to the design process. The rule of clarity is mastered by the experts, but not systematically applied. So it may also be for the rule of simplicity for a more complicated design problem. Finally, the factors that influence the product design other than costs, manufacturing and assembly are generally neglected by the designers.

## 5. CONCLUSION AND FUTURE RESEARCH

In this paper we presented the second study of a three-stage investigation of the designer at work, which aims at a better understanding and description of the later phases of the design process. An experimental approach proved to be appropriate to the purpose of the study. Six experiments were analyzed based on three dimensions: 1) the carrying out of basic design tasks, constituted by the designer's strategies and tactics; 2) use of rules, principles and guidelines; and 3) consideration of additional factors.

Among the designers a similar design process strategy was used. With this strategy, the designers used tactics that improved the efficiency of the design activities, but some weaknesses were also identified.

The experts' opportunistic behavior (going far into detail design when necessary) and most of the tactics they employed resulted in successful outcomes during the experiments. These new results support, among other things, our hypothesis that the design activities during the embodiment design and detail design phases can be refined by focusing on designers' activities.

The next step of the study is to validate the most important elements that can lead to an improvement of the later phases of the design process. This may be achieved to some extent through repeated experiments on the isolated elements. Experiments with a different design assignment should be performed in order to test the generalizability of our results. Alternatively, it would be interesting to try to refine the synthesis category, which is the core activity of the later phases of the design process.

The third stage of the investigation, the designer at work in his or her environment, should be carried out partly by using ethnography, partly through a survey focusing on the sensible points of the design process.

Finally, these findings should serve as the theoretical basis for the development of a more comprehensive design process.

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# Paper D

# Comparative Study of the Student's Design Process: Implications for the Teaching of the Later Phases of the Mechanical Engineering Design Process

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# Comparative Study of the Student's Design Process: Implications for the Teaching of the Later Phases of the Mechanical Engineering Design Process

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## Abstract

*Most methods that guide the designer through the later phases of the design process are general in nature, and it is up to the designer to organize the design work using the tools and techniques available. This process also relies greatly on experience, which is quite a challenge for students, who are mostly novices in the area. In a comparative study, the evolution of the experience and skills acquired by the students in performing design tasks during the embodiment design and detail design phases has been analyzed. The results indicate the main directions for improvement in teaching the later phases of the mechanical engineering design process.*

## 1. Introduction

The mechanical engineering design process — that is, the sequences of the activities required to design an artifact from its specifications to a product ready to be manufactured — that is taught to the student is often a decisive moment in his or her education. Of course, the mechanical engineering designer may use and learn several individual new techniques during a life-long carrier, but the way of organizing and sequencing his or her activities will tend to change more slowly and more difficultly, and is thus greatly determined by what has been learned at the university. The mechanical engineering design process, or design process for short, is deeply linked with the designer's experience, and is therefore time-consuming to assimilate and hard to change. Close attention must be paid to what the student needs to know, as well as to what he is ready to understand and assimilate and on which points the teacher must be resolute.

Little is actually known about how the student reasons and absorbs the concepts taught in class. The feedback provided by examinations helps to review the weaknesses of the students and consequently improve the course, but this is actually limited by the extent of the assignment task, which, in addition, only delivers the design process result and gives few insights into how the design task has been carried out. Atman *et al.* [1] studied the behavior of students more deeply by carrying out isolated experiments. Their successive studies on students now provide an initial mapping of the evolution of the students' capacity for designing from the stage of freshmen to that of seniors (last-year or graduate student). Nevertheless, these studies focus on the conceptual phase of the design process. This phase is crucial because the students need to acquire the skills of questioning the task assignment, searching for information, generating several alternatives and frequently iterating between the different steps of design (see also Adams *et al.* [2]). But the tasks that characterize the later phases of the design process (the embodiment design and detail design phases) are different. The designer has to gather the whole body of knowledge acquired in different disciplines (solid mechanics, materials, applied mathematics…) in order to embody and dimension the product-to-be. The designer also needs to be familiar with a whole set of techniques specific to each subproblem (see e.g. Pahl & Beitz [3]). This synthesis activity demands a different way of thinking.

This paper presents an observation of the evolutionary pattern of the students' ability to design by comparing juniors and seniors, based on an explorative study of the students' design process. This paper is partly based on a previous study reported in [4] and [5], which differentiated between the design activities performed by students and experts but did not differentiate between students.

Four dimensions of the design activity are investigated. The first one is the observation of the design activity viewed as a problem-solving process. The second and third are the design strategies and tactics that the students develop, or apply through the resolution of a design task. Finally, the techniques used by the designers are listed, considering the following categories: basic rules (clarity, simplicity and safety), principles or guidelines, and factors concerning the product life cycle (e.g. production, transport, recycling).

The implications of the findings for the teaching of the design process during the embodiment design and detail design phases are then discussed.

## 2. Related Work

A whole body of works focuses on, and reflects over, the difficulties of teaching and learning the design activity, taking into account the advancements in the fields of cognitive sciences, sociology and education ([2, 6-8]).

Concerning the problem-solving process, most of the research works in that area focus on the conceptual design phase. [9] showed that the more time students spent on problem scoping, the better the result. [10] showed that the design process could be described as an incremental process: the students understand the problem progressively and refine the alternatives (further developed in [11]). [1], further comparing freshmen and seniors, demonstrated that the students' design skills had improved (considering design outcome) with time. The design process was characterized by more information gathered, more alternatives developed, more iterations and more time dedicated to evaluation and decision. [12] studied the correlation between the quantity of sketches and design outcome by seniors. Casakin & Goldschmidt in [13] are working on the use of visual analogy as a problem-solving strategy. In a review published in [14], the main shortcomings observed for both students and experts reported were: early appearance and persistence of a kernel idea; design fixation (inclination to stick with early satisficing solutions); lack of flexibility in the designer's thinking behavior; superficial assessment, and subjective judgment.

In [4], a model was developed that describes the problem-solving pattern of designers (students and experts) during the embodiment design and detail design phases. 1) Contrary to the conceptual design phase, the problem scoping is very rapid, and most of the designers do not question the stated problem or come back to it during the design activity. 2) Very few alternatives are developed; the development of a solution is an interplay between the synthesis of the solution and its mechanical modeling. 3) Evaluation is made along the solution generation activity (and not at the end of the activity) by implicit or explicit criteria. 4) The detail drawing activity actually plays the role of control of the solution: everybody had to come back to the solution generation activity. This seems to explain why Yang [12] found that the presence of dimensioned sketches early in the conceptual design phase led to better design outcome. Detail drawing is the first moment where the designer needs to consider all dimensions, proportions, and interfaces.

There have been few observations of the designer's strategies and tactics during the embodiment design and detail design phases. Motte *et al.* [5] review the main findings on this design research area. Prescriptive strategies remain at a general level (e.g. [3, 15]) or highlight the difficulty of developing specific strategies and tactics, especially at the early embodiment design phase ([16, 17]). [5] reports that a common design strategy could be induced from the designers studied. A set of tactics has been extracted from observing the designers. Also weaknesses have been listed. Strategy, tactics and weaknesses are summarized in Table 1.

## 3. The teaching of the embodiment design and detail design processes

At Lund University, Sweden, students wishing to become mechanical engineering designers follow two years of general lectures (applied mathematics, physics, solid mechanics…) before specialization. In the third year, they learn about product planning and conceptual design in product development, as presented in [19]. Although the students learn tools and techniques useful for the embodiment design and detail design activities from the very first year, they really tackle the later phases of the design process during the last year, with the lectures on product architecture and form giving.

At this stage, the overall principle that is behind the teaching is the principle of "learning by doing" together with design cases study. Besides the general strategies mentioned in the literature ([3, 15]), there is not really any developed method that supports the designers for the embodiment design and detail design phases. The students learn a series of *basic rules*, *guidelines* and *principles* that help, but do not guide him or her through the embodiment and detailing of a technical system. Thus this is a study of different designs, training in different design tasks and projects (a six-month project or the M.Sc. thesis) that give the student the experience and sensitivity needed for designing.

The *basic rules* the designers need to have in mind during the design activity are *simplicity*, *clarity* and *safety* ([3, 17, 20]). Briefly, *Simplicity* means that the design must be simple to analyze and understand, with few components; *clarity* means that the behavior of the technical system must be easy to predict; *safety* means that the designer must take into account

**Table 1. Strategies, tactics and weaknesses (excerpt from [5]).**

| ***Strategies*** | ***Tactics*** | ***Weaknesses*** |
|---|---|---|
| General Strategy:<br>Rapid understanding of the problem.<br>Considering, very early in the process, the shapes of the parts and their interactions.<br>Concrete choice of materials.<br>Optimized choice of standard components.<br>Dimensioning of the joints.<br>Variations:<br>Dimensioning by experience or by mechanical analysis.<br>Often depth-first strategy.<br>Clear method that is loosely followed. | Think in terms of standard components.<br>Thinks in terms of concrete shapes.<br>Document the work.<br>Detail drawing.<br>Use of basic rules.<br>Criteria:<br>Minimization of costs,<br>Avoid unique part.<br>Take into account production.<br>Wait until late before using principles and guidelines. | Do not ask beyond the assignment.<br>Do not plan design activity (at an operational level).<br>Do not use a developed objective function.<br>Check activity considered as secondary.<br>Basic rules often followed only at the beginning of the design process.<br>No check for other factors than "costs" and "manufacturing/assembly".<br>Students:<br>Seldom check their design<br>Design knowledge not mastered (lack of experience) |

component reliability, function reliability, operational safety, and environmental safety [3].

The *guidelines* concern specific areas generally developed under the denomination of "design for X". Standard guidelines that help the designer dimensioning joints, like VDI 2230 [21], estimating costs, like VDI 2225 [22], or analyzing the quality and reliability of the product ([23-25]), can be included as well. Guidelines concern ultimately "ways of dealing with some physical and natural effects/phenomena like corrosion, wear and thermal expansions" [14].

Finally, the *principles* are practices, or rules of thumb, that have been proved very useful to an effective design (e.g. [26-28]). The first principle students usually learn is the following: "if a force or moment is to be transmitted from one location to another, with the minimum possible deformation, then the shortest and most direct force transmission path is the best" ([26, 3]).

This illustrates the extent to which the design process of the embodiment design and detail design phases is a patchwork of elements that the student learns. How and when to use these *basic rules*, *guidelines* and *principles* is left up to the student. By comparing juniors (students that are learning form-giving and product architecture) and seniors (students who have completed the course and have almost "one year experience"), this paper gives insights into the progress made by the students. This comparison, made through the four dimensions mentioned earlier — problem-solving process, design strategies, tactics, and techniques used, and coupled to the comparison between students and experts developed in [4] and [5] — can serve as a basis for improving the teaching of the process of the embodiment design and detail design phases.

The next section presents the methods used to observe the evolution of the students' design skills.

## 4. Methods

Two methods were employed. This paper is principally based on the first: the analysis of experiments where designers were asked to solve a design task. On the fringe of these experiments, sketches of a design task carried out by juniors attending the lecture on form giving have been analyzed.

### *4.1. Controlled experiments*

Studying the designers under controlled experiments makes it possible to focus on the design process and monitor factors that could bias the analysis. Six experiments have been carried out, with three experts and three students (two seniors and one junior). The junior was about to begin the course on form giving, while the two seniors were completing their M.Sc. theses. The designers had to embody and dimension a support for a hydraulic cylinder. The support had to stand beside the installation (see Figure 1). The full experiment protocol is described in [29].

The designers were videotaped and were asked to "think aloud", that is, to describe what they were doing. What they said was then transcribed and analyzed by the verbal protocol analysis method [30]. [31] demonstrated verbal protocol analysis as a relevant method for studying students' design activity. Verbal protocol analysis consists in the segmentation of the verbal protocol into episodes that represent a single action. The episodes are then analyzed with the help of a set of categories, or coding schemes, each representing a basic action. The repetition and the sequences of the basic actions are then interpreted.

A coding scheme has been developed for the study of the design activity modeled as a problem-solving activity [4], and another coding scheme has been developed for the study of the designers' strategies and tactics [5].

Each time a designer applied a basic rule, guideline or principle, the nature of this basic rule, guideline or principle and the moment it was applied were reported. So it was with the factors the designers took into account during the design process. These factors were adapted to the design task of the experiment from those given in [3] (p. 206), among others: manufacturing/assembly, transport, operation, recycling, costs, schedules.

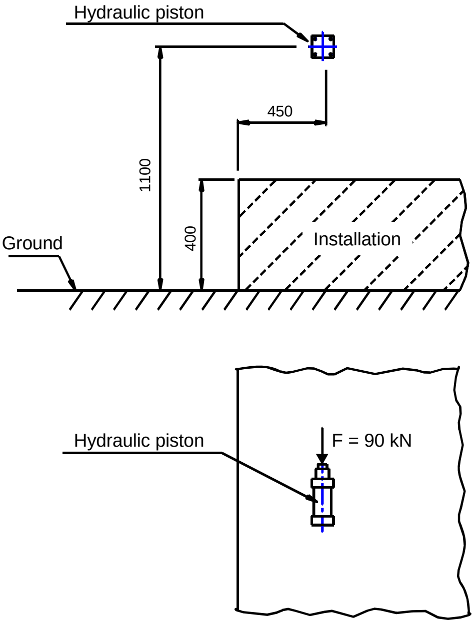

**Figure 1. Sketch of the problem delivered with the assignment [29].**

### *4.2. Design task sketches*

The same design task as the one used for the experiments was given to the students as an obligatory examination task. They had three weeks to submit their solution (a fully dimensioned support for the hydraulic cylinder) and the theoretical time they had at their disposal to work on the problem, given that the volume this course represented in the study curriculum was equivalent to 3-4 days of fulltime work. The day the design task was distributed and discussed in class, the students were asked to sketch the first idea they had for a solution. The drawing of the final solution delivered after three weeks could then be compared to the first sketch. This sketch could even be compared to the first sketches of the designers who participated in the experiments.

## 5. Results and discussion

The results are presented following the four dimensions mentioned above: problem-solving activity, design strategies, tactics, and techniques used (basic rules, guidelines, principles and other factors). The results from the comparison of the design sketches are presented later.

### *5.1. Problem-solving activity*

Once the verbal protocols are coded, that is once an action or category has been attributed to every episode, the sequence of problem-solving actions can be visualized. Figure 2 shows the sequence of actions performed by the junior; Figure 3 shows the sequence of actions performed by a senior. The interruptions that can be observed on the charts correspond mainly to social behavior episodes, when the designer loses attention, justifies his faults or simply relaxes [29]. The episodes that could not be coded (because of bad recording for example) represent a negligible part of the total number of episodes. In this section, the overall strategy developed by the designer is discussed first, and then the individual episodes.

If on the whole the junior has the same strategy (see section 2) as the other designers, his progress was very loosely structured. The student went thoroughly through the task assignment, but rapidly lost focus on the expected results of the assignment (among other, a detailed sketch of a solution), before coming back to it. The seniors, to that extent, acted like the experts. Nevertheless, the interplay between synthesis and mechanical modeling, followed by dimensioning, which is described in [4], was present in the problem-solving activity of the junior. This seems to indicate, as the student had almost no experience, that this pattern of actions is acquired "naturally" or prior to design lectures, that is, in any case, not acquired by experience.

The junior was the only designer who came back to problem understanding (categories Irp, Es, Sp in Figure 2) late in the design process. The student made a thorough rereading of the problem statement, checking if his design process and solution corresponded to the requirements. However, the junior developed what Bender & Blessing [32] called *adhocism*. The junior tried rather to adapt the problem to his solution and his skills (see also [4]). The problem understanding episodes that can be seen after the first half hour often

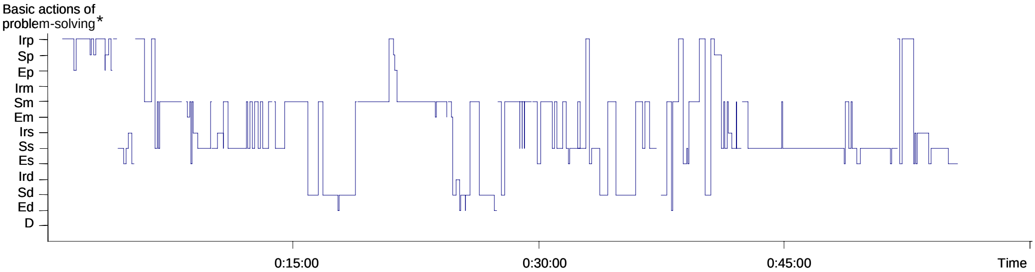

**Figure 2. Problem-solving activity of the junior.**

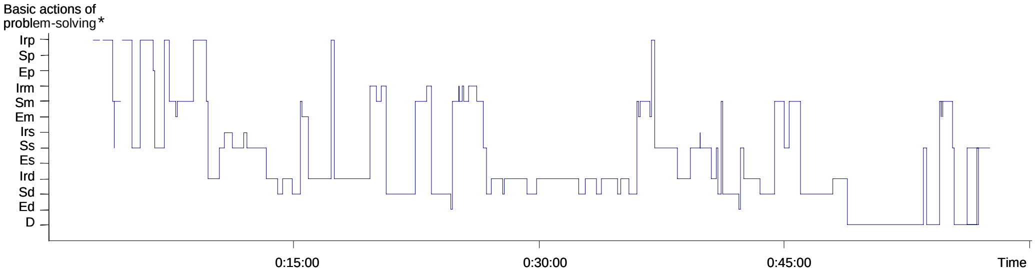

**Figure 3. Problem-solving activity of a senior.**

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* Sp: problem reframing; Sm: mechanical modeling of the solution; Ss: Synthesis of the solution; Sd: dimensioning; D: detail drawing; Irp, Irm, Irs, Ird: information search episodes concerning Sp, Sm, Ss, Sd respectively; Ep, Em, Es, Ed: evaluations/decisions concerning Sp, Sm, Ss, Sd respectively (see [4]).

became questions that were preliminaries to a kind of negotiation with the experimenter. That the junior did not go into detail drawing is an illustration of this behavior; the interpretation of the problem statement led to the fact that his drawings — and then solution dimensioning — did not need further refinement (see Figure 6). The seniors did not behave this way. They sometimes admitted the difficulty of the exercise but never tried to change the assignment.

The information search episodes (Irp, Irm, Irs, Ird, see Figure 2) of the junior were fewer in number and time than the seniors, but this was largely due to the fact that the junior did not try to dimension everything. Thus he did not have to search for profiles, materials, etc. Most of the information search episodes were dedicated to problem understanding.

In comparison with the seniors, the junior spent much more time on mechanical modeling (Sm) (30% of the time against 12% for the senior, whose problem-solving activity is represented in Figure 3). This was clearly due to a lack of knowledge and experience. The seniors spent more time on Sm than the experts, but that was rather due to the fact that the seniors' solutions were more complicated [29].

There were more evaluation moments (Ep, Em, Es, Ed), both in time and number, than for the seniors. But this cannot at present be interpreted as a characteristic evolution between juniors and seniors; more experiments are needed in this area. The evaluation episodes of the juniors are indeed similar to the evaluation episodes of the experts; but due to the radically different sequences of basic actions that they had, it would be harsh to try to find a correlation between the evaluation episodes and the evolution of the designers' behaviors.

### *5.2. Design strategies and tactics*

The second and third dimensions studied were the design strategies and tactics applied by the designers. This was done with the help of a new coding scheme. Figure 4 represents the sequence of the basic design tasks performed by the junior; Figure 5 represents the sequence of the basic design tasks performed by a senior.

The strategy deployed by the experts is presented in Table 1. One senior adopted the same pattern, while the other one, who did not dimension his solution, skipped several points (optimized choice of standard

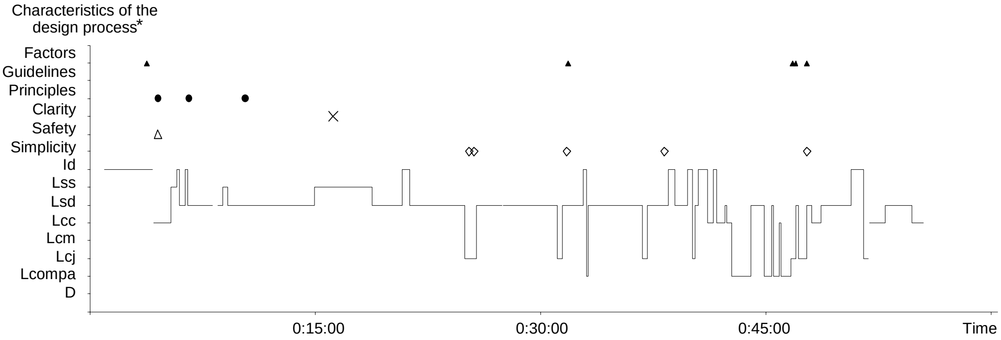

**Figure 4. Basic design tasks performed by the junior.**

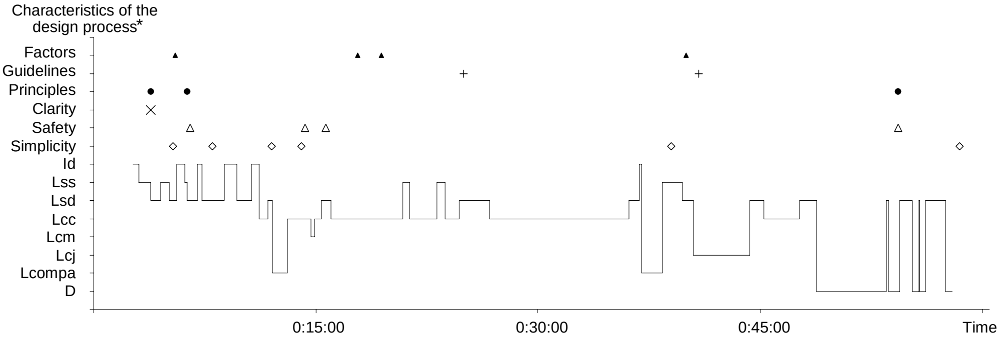

**Figure 5. Basic design tasks performed by a senior.**

components, for example). The junior did not try very hard to structure his process. The two seniors began by embodying the support, as did the experts, although more loosely: they did not attach importance to the interfaces between the parts and the environment. The junior began with the choice of the mountings of the hydraulic cylinder (Lcc episodes at the beginning of the design process, see Figure 4), before beginning the embodiment.

The junior did not try to choose standard components. The beams of the support are supposed to be larger at their base (Figure 6). This leads not only to manufacturing difficulty, but the dimensioning itself becomes very complex. The necessity of simple and clear designs (which are by the way a consequence of the *simplicity* and *clarity* rules, see below) that make calculations easier has been integrated by the senior, who chose standard I-beams. Still, the seniors seem to have neglected the interfaces problem. If we compare the design made by a senior (Figure 7) and the design made by an expert (Figure 8), the interface problems are treated from the beginning by the expert, while they are neglected by the seniors who, like the junior, develop specific parts.

It is worth mentioning that by the end of the experiment the junior proposed the use of I-beams, but still maintained his requirements (larger at the base). He actually postponed the problem, assuming that someone else would take care of it (maybe the manufacturing department). An interesting question arises concerning the perception of the concept of (mechanical engineering) design by the students. In this case, the creative view of design seemed to be emphasized to the detriment of a more concrete perspective: a design solution *must* work. The seniors, however, take this into account: the problems they neglected were due to lack of experience (the interface problems, for example), not to conscious postponement of the problem. This is probably partly due to design cases studied in class (design cases show how every detail is

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* Id: problem identification; Lss: scale of spatial constraints; Lsd: synthesis; Lcc: choice of components; Lcm: choice of material; Lcj: choice of joints; Lcompa: ensure compatibility/interface; D: detail drawing (see [5]).

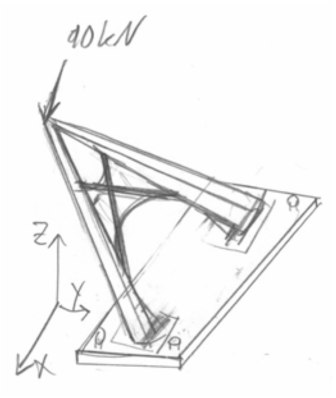

**Figure 6. Junior's embodiment of the support.**

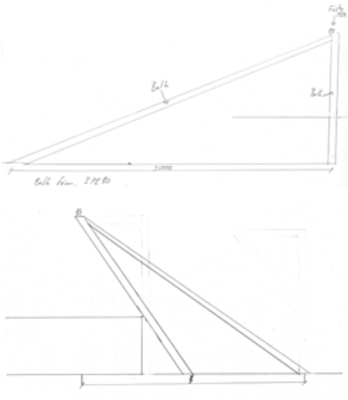

**Figure 7. Embodiment of the support of one senior.**

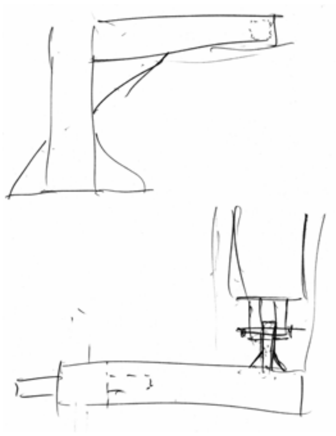

**Figure 8. Embodiment of the support of one expert. [29]**

important), but also to the 6-month the product development project and M.Sc. thesis that follow, and which are done in collaboration with industry.

Surprisingly, the junior did not document his work very much. It was assumed that two years of physics and mathematics would have given some rigor in the task performed, but this was not the case. This may be due to the fact that, the design process being loose, the junior did not know what was important to write down and what was not. The seniors had the same behavior. This resulted in loss of time for both.

Finally, the seniors (and the experts) always had in mind one function to optimize while designing, namely the costs. The experts had a more sophisticated model, taking into account manufacturing and assembly.

### *5.3. Basic rules, guidelines, principles and other factors*

The junior was led by the *simplicity* rule as many times as the senior (around 5 times in one hour). However, this rule was used mostly when the designer had trouble with his design or when dealing with details. This was sometimes the case for the senior, but the rule was used for decisive elements of the system. Like the experts, the seniors let the simplicity rule constrain their design. This rule seems to be quickly assimilated by the students.

The rule of *clarity* is the least understood. The junior used it once, but so did the senior. Clarity is a difficult concept that is taught through design cases. There may be a need to teach it in a different manner so that the student assimilates it more rapidly.

The *safety* rule was used only once, against three times for the seniors. The experts, on the other hand, used this rule frequently. There seems to be a need to insist on the dimensions of the safety rule (component reliability, function reliability, operational safety, and environmental safety).

Seniors and experts overall used the basic rules at the beginning and at the end of the design experiment. They have in mind at the beginning the necessity of simplicity, clarity and safety, but forget about them as the design progresses. They tend to stick to parts of the solution that they try to dimension, rather than simplifying or changing. At the end of the experiment, the designers did a detail drawing of their solution and then, when hidden faults became visible, they had to come back to synthesis and use the basic rules again [5]. The junior shows a rather continuous use of the basic rules. This is due to the fact that, as mentioned earlier, his design process was more loosely structured: the junior sometimes began to be interested in a new part of the solution, and then once again began the synthesis (and mechanic modeling activity).

The junior did not apply any *guideline*. One senior applied 2 guidelines (one for buckling analysis, one for welding). This tends to show that the students understand the importance of the guidelines. It is worth noticing that the seniors would have used FEM, if these tools had been available, instead of estimate calculations.

The students used the *principles* of direct force and stability [3]. The design task of the experiments was not adapted to the use of many different principles. A new experiment with a different design task needs to be set up in order to observe how well the students assimilate the principles they learn.

The junior did consider more *factors* than the seniors: production/assembly, costs, maintenance and dismantling, while the seniors only considered production/assembly and costs. However, the junior considered these factors for details, while the seniors used them as clues for designing. Many other factors (see section 4.1) important for the quality of the design outcome were nevertheless neglected. This holds as well for the experts. The checklist presented by Pahl & Beitz [3] needs to be more present during the teaching of the later phases of the design process.

### *5.4. Design Sketches*

Parallel to the experiments, other students attending the lecture on form giving were asked to draw a sketch of their first idea. This was compared to their final design. Figure 9 is the first sketch of one student. Figure 10 is the final solution he delivered for the examination. As can be seen, the design is far simpler (fewer parts, standard components) and clearer (the support is easier to analyze). The result was similar for most of the other students. This is without doubt largely due to the analysis and calculation problems the students would have had with their first design, illustrating the strength of the "learning by doing" method.

However, many designs remained incomplete: there is no fixation for the hydraulic cylinder; there is no fixation on the ground. The welding of the I-beam on the rounded corner of the VKR-beam (see Figure 10) can be problematic. This confirms our previous remarks on the necessity to emphasize the interface problem.

## 6. Conclusion

In this paper the evolution of the design skills and experience of students during the later phases of the design process has been analyzed. The design processes of a junior and two seniors were compared along four dimensions: problem-solving process, design strategies, design tactics and application of basic rules,

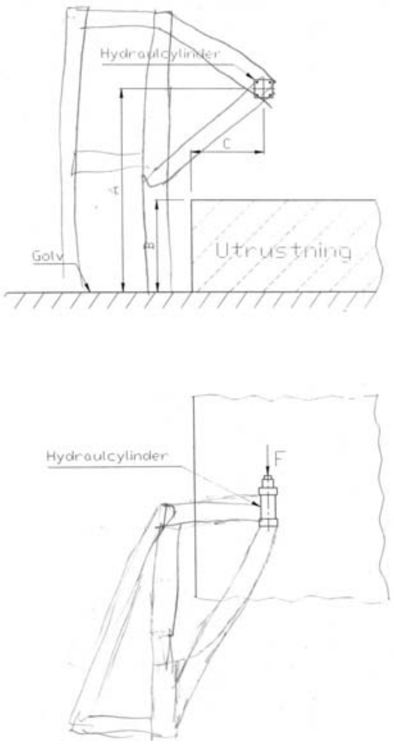

**Figure 9. First sketch of a student.**

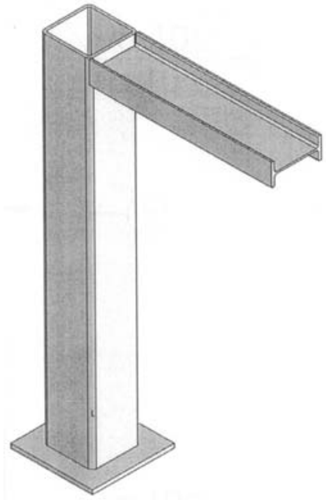

**Figure 10. Final solution delivered by the same student.**

only explorative, due to the small number of designers studied, but the benefits and shortcomings of teaching by "learning by doing" and design cases study could be highlighted.

These teaching methods tend to suppress the *ad-hocism* noticed by the junior. The seniors focus more on the vital parts of the solution; they apply guidelines, and the problem-solving activity is not as loose as that of the junior observed. The interplay between synthesis and mechanical modeling seems already acquired by the student prior to the course.

Nevertheless, teaching a list of rules, principles, and guidelines with a too-general design process is not effective. The seniors neglected several points that are taken into account by the experts: problems of interface, early concretizations, and systematic choice of standard components. Moreover, both students and experts did not question the problem sufficiently, and developed very few alternatives, although they had knowledge and experience of conceptual design methods. Both took into account only a few factors (production/assembly, costs…). There is a need to develop and teach a more stringent prescriptive design process to guide the designer through the embodiment design and detail design phases, at least during the early embodiment design phase.

To this major point, other findings have been extracted from the experiments that must be taken into account for teaching the later phases of the design process. If the students rapidly assimilate the simplicity rule, the rules of safety and clarity need more time. This must be emphasized during the teaching of these rules. The students observed had a tendency not to document their work, which led to a loss of time. This can be seen as a personal organization problem, but a coupling to the vagueness inherent in design assignments cannot be excluded. The factors listed by Pahl & Beitz [3] were insufficiently taken into account.

Finally, several points need to be further investigated, mainly the assimilation and re-use of principles, and the carrying-out of evaluations of the solutions by the students.

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