A study of the designer's cognitive processes during the later phases of the engineering design process

Motte, Damien; Andersson, Per-Erik; Bjärnemo, Robert

Published in:
Proceedings of the 8th International Design Conference - DESIGN'04

2004

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Motte, D., Andersson, P.-E., & Bjärnemo, R. (2004). A study of the designer's cognitive processes during the later phases of the engineering design process. In D. Marjanović (Ed.), *Proceedings of the 8th International Design Conference - DESIGN'04* (Vol. DS 32-2, pp. 421-428). University of Zagreb and Design Society. http://www.designsociety.org/publication/19784/study_of_the_designer%E2%80%99s_cognitive_processes_during_the_later_phases_of_the_mechanical_engineering_design_process

Total number of authors:
3

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

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

Study of the Designer's Cognitive Processes During the Later Phases of the Mechanical Engineering Design Process

Damien Motte, Per-Erik Andersson, Robert Bjärnemo

Design process, embodiment design, detail design, cognitive aspects, problem solving process, verbal protocol analysis

1. Introduction

During the last fifteen years, an increasing number of research studies have been focusing on the impact of human cognitive processes on the mechanical engineering design process. These results have improved our knowledge of the designer's abilities, as well as of his cognitive limitations. The findings indicate that these limitations restrict the applications of commonly accepted prescriptive methods, and that support is needed (computer-aided or others). These studies have mostly concerned the conceptual phase of the design process. On a conceptual level, the problems presented to the designers are ill defined and susceptible to adding considerable biases to the process of finding a solution. There is also great need of understanding creativity. Finally, the decisions taken at this phase are crucial for the further development of a product.

Yet the later phases of a product design are still important, concerning the time they take, the consequences they have on the future assembly and production of the product, and the costs they involve. Thus there is a need to explore the designer's cognitive processes and tasks during the embodiment design and detail design phases, that is to delimit the specificities, constraints and needs of the later phases of the design process, as has been done so far with the conceptual design phase. In the present paper, we focus on the problem-solving process — strategies and basic steps — around the synthesis activity. Synthesis is one of the core activities of embodiment design and detail design, the "creative" part where the shapes, layout, etc. are determined.

The method applied, the verbal protocol analysis (VPA), needed to be adapted to the embodiment and detail design phases. Thus, this paper presents the development and use of an adapted methodology to the study of the later design phases, and the first results obtained from 6 experiments.

The paper is organised as follows. The first section below presents the background of the study (theory, definitions of embodiment design and detail design, related works). The experimental method, with emphasis on the new coding scheme for VPA, is presented in the next section. This is followed by the results that have been obtained from the 6 experiments. Finally, future research that should be undertaken in this area is presented.

2. Background: the study of the cognitive activities in design

2.1 Theory

There is a consensus that the nature of the design process is problem-solving activity independent of the design phases (conceptual design, embodiment design or detail design) — the activities of understanding the task, generating solutions, evaluating and selecting them (see e.g. [Hubka 1976], [Pahl & Beitz 1996], [Ulrich & Eppinger 2000]). The study of problem solving in the design activity seeks to find templates of behaviours, constraints and needs of designers during the problem solving process. Studies related to the problem-solving process concern creativity, knowledge, memory and external supports to design (drawing, sketching, computer-based support systems).

The most widely used method for studying the problem-solving process is the so-called verbal protocol analysis, where the subjects are asked, during an experiment that varies from one to four hours, to think aloud, i.e. to describe aloud what they are thinking while they are solving a design problem [Ericsson & Simon 1993]. The other main method used is sketch analysis, which rather concerns creativity and problem visualisation, and thus was not used in this study. The number of experiments carried out in association with VPA for most of the studies surveyed in [Motte & Bjärnemo 2004] varied from one to ten. This slight number of experiments is due to the explorative nature of this kind of research and the richness of data that is generated by this approach. Statistical aspects are seldom considered.

The main findings from the studies of the cognitive aspects of problem solving in the design activity, which are by nature valid for engineering design in general, are the following: dealing with early appearance and persistence of a kernel idea, failure to search for alternative solutions, design fixation (inclination to stick with an early satisficing solution), superficial assessment, subjective judgment, and lack of flexibility in the designer’s thinking behaviour (see [Motte & Bjärnemo 2004] for an extended review).

2.2 Definitions of embodiment design, detail design and synthesis

In earlier literature (e.g. [Hubka 1976], [Pahl & Beitz 1996]) embodiment design was considered to be the complete determination of the technical system arrangement (anatomical structure), component form giving, materials, and manufacturing methods. Later publications emphasize product architecture and decomposition into chunks (e.g. [Ulrich & Eppinger 2000]).

With some variation among the authors, detail design is constituted by the complementary tasks that are not considered in embodiment design. Thus, detail design is considered here arbitrarily to be the documentation part of the later phases of design (e.g. drawings) as well as the calculations that are based on standards, like final welding calculations. This definition of detail design may seem to be restrictive, but reflects the thought of most of the literature.

Synthesis, i.e. combining the retrieval and the comparison of the relevant knowledge (mechanical, technical…) with the current design problem, is here the putting together of the elements to fulfil the requirement from the design problem at hand. Synthesis is considered creative in the sense that it generates something new, not necessarily original, but that did not exist before. Creativity is more restricted in the later phases of the design process than in conceptual design, but has the same importance.

2.3 Works related to the problem-solving process within embodiment and detail design

A recent literature survey aiming at representing the state-of-the art of research on cognitive aspects of the design activity has been published elsewhere [Motte & Bjärnemo 2004]. As mentioned above, most of these studies were dedicated to conceptual design. [Fricke 1999] deals partly with embodiment design, but focuses on task clarification. The study of [Ball *et al.* 1998] considers embodiment design, but in the field of electronic engineering, with which comparisons with embodiment design in mechanical engineering are limited (little or no layout problems, for example). Thus no study is known that deals with the purpose of this paper. This has led to the need for an adapted coding scheme for embodiment design and detail design, which is presented in the next section.

3. The experimental method

The first part of this section deals with the procedure used during each experiment. The new coding scheme is then presented.

3.1 The procedure

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 had followed the product development–mechanical design syllabus. Comparing students to experts reveals the gap of knowledge and competence between the former and the latter.

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, manipulated by a second experimenter, recorded the sequence, following the focus and the actions of the subject.

Based on the ethical principles used in sociology and psychology, a secrecy agreement was co-signed by each of the subjects and experimenters. This protects the subjects from being identified by a third party, but allows any researcher, who would question the results, to have access to the tapes, assuming the signature of a new secrecy agreement. Such a process assures 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 had 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 by the side of this installation (see Figure 1). The specifications of the piston were given in the assignment. This design task, then, was relatively well defined, and corresponded to what one can expect from a similar situation in an industrial project. Intentionally, the form giving aspect was not very complex, so that the subjects had the time for both synthesis and dimensioning. Finally, there was a short interview in which the subjects were asked to evaluate their design and the experiment.

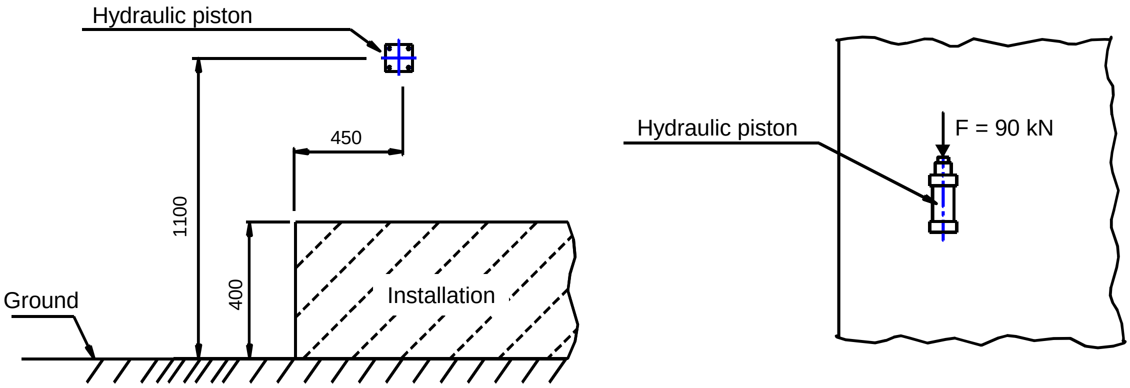

Figure 1. Sketch of the problem delivered with the assignment

3.2 The coding scheme

3.2.1 Specificities of embodiment design and detail design

Like conceptual design, embodiment design and detail design are problem-oriented. While the former emphasises novelty and creativity during the process, while the later focus on the rigorous study of each element 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 a survey of the relevant papers referenced in [Motte & Bjärnemo 2004], the coding schemes developed for conceptual design were considered as unsuitable (see e.g. [Atman et al. 1999], [Ball et al. 1998], [Purcell et al. 1996]). In order to find a new coding scheme, the first experiments were analysed 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), a third researcher, with no knowledge of the coding schemes, was added to the group. It turned out that most of the actions of the subjects, besides information research and evaluation, were distributed among a mechanical description of the problem, a synthesis activity and a dimensioning activity. Sometimes it was observed that the designer consciously organised his or her work (e.g. numbering of the sheets, reorganisation of the desk). These reflections were used as a basis for the coding scheme.

3.2.2 The coding scheme

The final categories of the coding scheme are described in Table 1. Apart from the categories described above, attention was directed to the social behaviours that could bias the designer's problem solving process. The protocol was then structured as Table 2. The next three columns are the protocol itself, written from the tapes, that concerns the verbal exchange of the subject and the first experimenter and the subject's actions and focus. In the last column, "others", remarks concerning the experiment and possible improvements were reported.

Table 1. Categories of the coding schemes

Category		**Description**
Ir	information research	Concerns the time segments where the subject asks the experimenter for complementary information.
Sm	mechanical description, model of the solution	Concerns the time segments where the subject describes the solution in mechanical terms (force, moment; strain, stress; buckling; etc.)
Ss	synthesis	Concerns the time segments where the subject creates the form and layout of the support.
Sd	dimensioning	Concerns the time segments where the subject dimensions the support.
E	evaluation	Concerns the time segments where the subject evaluates his work.
D	drawing	Concerns the time segments where the subject documents his or her work by a detail drawing.
O	organisation	Concerns the time segments where the subject organises his or her way of working.

Table 2. Protocol table

Time	Problem Solving Process	Basic rules	Social behaviours	Verbal protocol	Motor activities	Focus	Others

3.3 The protocol analysis process

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

4. Results

The experiments were coded, and the categories of the coding scheme presented above were used as the basis for the analysis of the design process of the subjects. It was then possible to obtain a chart that gave the pattern of activities of each designer (e.g. Figure 2). From the coded protocol, the charts and the drawings, it was possible to give a first description of the overall problem solving strategies, the synthesis moments and the role of the other basic design steps represented by the coding scheme categories, which are presented below. The results given are a first analysis of the experimental data. They permitted to confirm the relevance of the new coding scheme. Additional results will be available when a closer coding scheme will be developed.

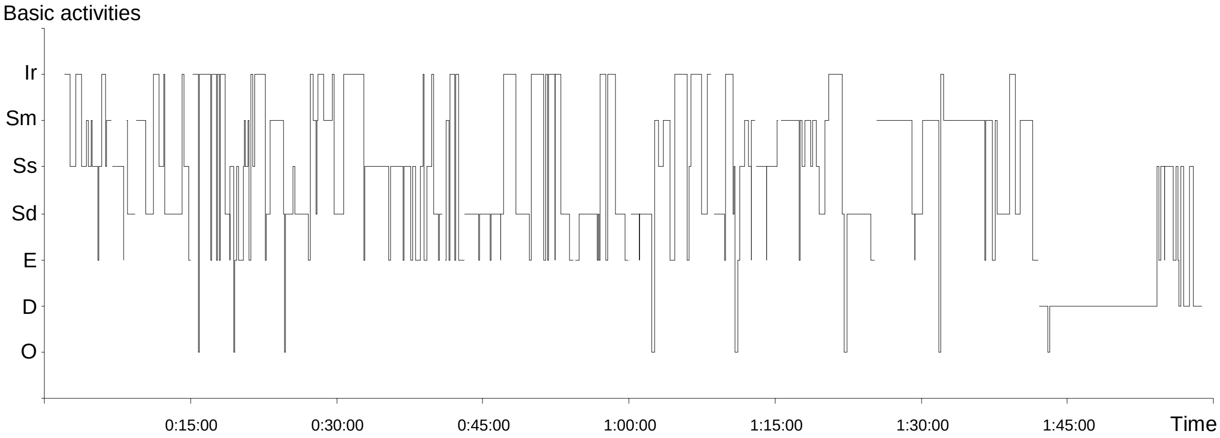

Figure 2. Design steps of an expert

4.1 Problem solving strategies

There is an overall similarity in the problem-solving process of all the designers. They understood the problem relatively quickly, rarely developed more than two different alternatives, rapidly selected one, but then took time to study it and modify its shape (synthesis). It is difficult to address reasons for the scarcity of alternatives. It may be due to the early fixation on one solution, as is proposed in the literature. But it may be due as well to the fact that the problem is relatively well defined, and thus does not require a large number of alternative solutions. There is a great difference at this level between conceptual design and embodiment/detail design: the designer can relatively easily see whether "it works" or not. This quickly reduces the number of solutions, but the designer has the temptation to stick to a "satisficing" [Simon 1993] but inferior quality solution.

Amazingly, the first mechanical analysis of the problem made by the subjects was always very short. The longest, made by an expert, lasted one minute (interrupted by information research). The others generally began directly with synthesis, and afterwards verbally evoked the analysis of their first idea, and that took no longer than 5 seconds. Even if it is certain that a mechanical analysis cannot be separated from a solution, no other mechanical configuration than the first one was considered.

The similarities between students and experts end there. At that step, experts are already speaking of I-beams, pipes, etc., i.e. in terms of standard design components. On the other hand, the students remain on an abstract level and continue to reason with the classical beam they studied in solid mechanics. The first concrete elements are initially evoked by the students after 10-15 minutes. The problems linked to the geometric specificities of the beam, and especially the interfaces between them and other elements (the piston, the ground) generally received attention after 25-30 minutes. These specificities are either neglected or solved with a particular, not standard device. In Figure 3, the differences between the first sketches of an expert and a student (from the first ten minutes) are illustrated. The fixation of the piston to the support is schematic by the student, while it is really detailed and based on existing elements by the expert.

Rather surprisingly, even if the experts had quite the same behaviour during the experiments, they had different approaches concerning the dimensioning. Two of them made no calculations and set up all dimensions based on their own experience. Two students did not dimension at all; they rather refined their design. Their tactic was, once the basic principle of the support was found, to find ways to strengthen it and make it safer (diminish the risk of collapse). It is possible that basically the students did not feel sure enough of themselves to begin the dimensioning; it can be due as well to the limited time of the experiment, but the behaviour of the students showed that they were attracted by the creative part of the embodying process. The experts began the dimensioning relatively quickly (after around ten minutes) but only after having designed a relatively detailed solution. In this detailed system, the mechanical description of all components was known, as well as the interactions between all components. In fact, the artefact only needed to have the dimensions to be manufactured.

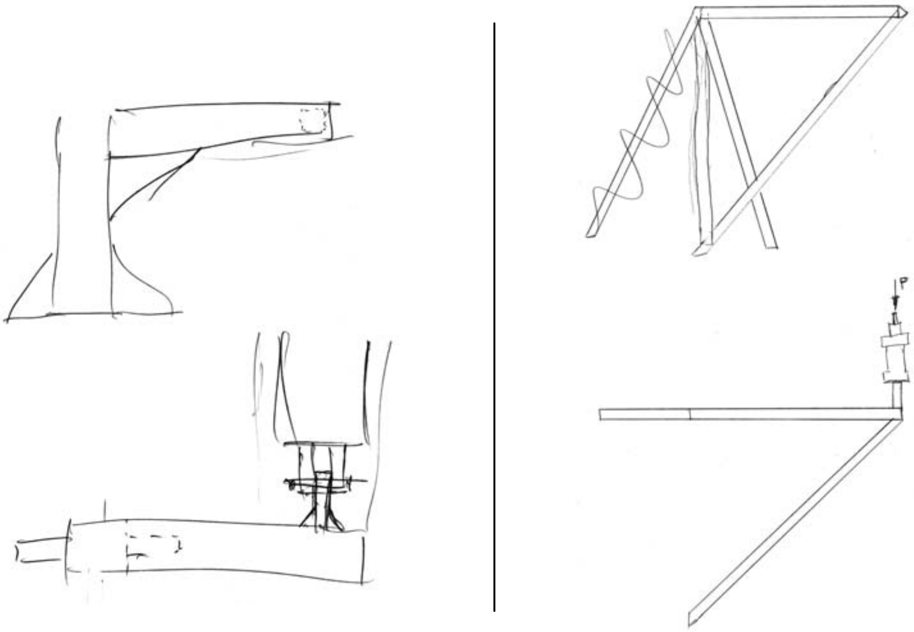

Figure 3. Examples of solutions of an expert (left) and by a student (right)

That did not, however, prevent the experts from returning to a mechanical description of the artefact before every dimensioning. That was true for the expert that dimensioned with the help of formulas as well as for the two others.

4.2 Synthesis

The experiments permitted characterizing the synthesis activity in detail.

First the chart showed that the mechanical description or analysis was very often evoked after the synthesis part. This does not mean that the subject did not previously make any mechanical analysis, but that the idea for a solution comes really fast and is then followed by a more sophisticated, conscious mechanical description, which plays more or less a role of verification. Moreover, the fact that synthesis is accompanied by a mechanical analysis confirms that creativity in embodiment design and detail design is “reasoned”, that is the result of a rationale based on “the retrieval and the confrontation of the relevant knowledge” mentioned above. The time segments where the synthesis does not comport any mechanical description occur when the activity is the prolongation of an earlier one. The students had more synthesis parts without mechanical analysis counterparts.

On the other hand, synthesis was not often followed by evaluation. The designers continued to build their solution with the implicit feeling of being right. Evaluation occurred only when a problem came up, and was astonishingly rapid.

Finally, concerning the content of the synthesis activity, the students remained for a long part of the experiment under the abstract level. This was a typical lack of experience. The interviews showed that students had not the same level of experience. The less experienced the student was, the more complicated the solution was.

4.3 The basic design steps

The “information research” activity did not vary significantly between experts and students. Those who calculated the dimensions needed more information on the components used. Concerning the content of the information, no difference was observed between the students and the experts, contrary to the experiments in conceptual design that showed that subjects with experience asked for more information about the assignment. Neither students nor experts requested more information than they strictly needed to design the artefact.

Concerning the role of the “mechanical description”, mentioned above, one supplementary point was observed. All the students developed an artefact 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 (see Figure 3). This seems to show that students tend to reason more easily in terms of force than in terms of moment. This remark, if validated, would mean that a parameter that reduces the scope of solutions is of a lack of experience, not in design, but simply in solid mechanics.

“Dimensioning” was relatively often accompanied by a mechanical description of the solution by the experts. As for “synthesis”, this was less systematically the case for the students who did it, and this seems to be because they “stick” more often to the earlier mechanical description they gave of their solution.

The periods dedicated to “evaluation” were really short. Most of them were between three and seven seconds. If this is obviously normal for the dimensioning activity (the result obtained is simply compared to the desired one), this is more difficult to interpret in the case of the synthesis activity.

The “organisation” category, not linked to the problem-solving activity, was nevertheless present in half of the experiments. Although the experts were more structured concerning the problem-solving process, no relation could be discerned between the two activities. Organisation of one’s work was mostly of a personal nature.

“Drawings” is not a problem-solving activity either. However, it is the documentation part in detail design, and this played a significant role in the experiments. The first detail drawing is of great importance for both students and experts. Indeed, it is at this moment that the dimensions are really proportional, that the smallest detail must be made “real”, and all the subjects needed to come back, at one time or another, to the synthesis activity.

The social behaviours moments of the experiments represent the majority of the interruptions in the problem solving process that are visible on each chart (see Figure 2). They were generally short (around ten seconds). Some occurred in a moment of lost of attention, after 30-45 minutes of work, which is interpreted as relaxing moments. Others were justifications of the errors they had made during works.

5. Conclusion and future research

In this paper, a new coding scheme was proposed, which allowed studying problem-solving processes in embodiment design and detail design. The six experiments gave us insights into the problem-solving strategies used by designers, their behaviour during each design step, and a better description of the synthesis activity.

This study confirms that embodiment design and detail design have specific cognitive aspects different from conceptual design. Among other things, it is important to notice that everybody began quickly to design a solution, with little time dedicated to its mechanical description, but that experts always had in mind the manufacturability of their product. The evaluation periods were very short as well. A majority of experts relied on their experience for the dimensioning activity. The detail drawing is a source of information: this has been a way for all subjects to see the defects that could possibly lead to a totally new analysis.

This study was explorative in nature. The coding scheme will be refined for future research in order to fully exploit the available data. The number of experiments will be increased in order to validate the results. Moreover, several aspects of the embodiment design and detail design that were not raised in this paper require further attention, in particular the two following points. First, the tools and techniques that support embodiment design and detail design — principles, guidelines, and especially the basic rules clarity, simplicity and safety —need to be studied more deeply in order to determine the support (computer-aided or not) that they would need and the influence on their teaching. Then, while the designers’ problem-solving activities described above represented the “operational” aspect of the embodiment design and detail design phases, these phases must now be studied as a process and the obtained results compared to the normative procedures.

References

Atman C.J., Chimka J.R., Bursic K.M., Nachtmann H.L., "A comparison of freshman and senior engineering design processes", Design Studies, Vol.20, No.2, 1999, pp. 131-152.

Ball L.J., Maskill L., Ormerod T.C., "Satisficing in engineering design: causes, consequences and implications for design support", Automation in Construction, Vol.7, No.2-3, 1998, pp. 213-227.

Ericsson K.A., Simon H.A., "Protocol analysis: verbal report as data" (Rev Ed), MIT Press, Cambridge, 1993.

Fricke G., "Successful approaches in dealing with differently precise design problems", Design Studies, Vol.20, No.5, 1999, pp. 417-429.

Hubka V., "Theorie der Konstruktionsprozesse", Berlin/Heidelberg, Springer, 1976.

Motte D., Bjärnemo R., "The Cognitive Aspects of the Engineering Design Activity – a Literature Survey", Proceedings of the TMCE 2004, Horváth and Xirouchakis, Lausanne, Switzerland, 2004 (accepted).

Pahl G., Beitz W., "Engineering Design – A systematic approach" (2nd Rev Ed), Springer, London, 1996.

Purcell T., Gero J., Edwards H., McNeill T., "The Data in Design Protocols: The Issue of Data Coding, Data Analysis in the Development of Models of the Design Process", in "Analysing Design Activity", ed. by Cross, N., Christiaans, H. H. C. M., Dorst K. H., Wiley, Baffins Lane, England, 1996, pp 225-252.

Simon H.A., "The sciences of the Artificial" (3rd Ed), MIT Press, Cambridge, MA, 1996.

Ulrich K.T., Eppinger S.D., "Product Design and Development" (2nd Ed), McGraw-Hill, London, 2000.

Damien Motte
Lund Institute of Technology at Lund University,
Division of Machine Design at the Department of Design Sciences
Box 118, 221 00 LUND, Sweden
Tel. +46 46 222 85 13, fax. +46 46 222 80 60, e-mail: damien.motte@mkon.lth.se