Elements for improving the teaching of the later phases of the mechanical engineering design process

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

Published in:
Proceedings of the 15th International Conference on Engineering Design - ICED'05

2005

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

INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 05 MELBOURNE, AUGUST 15-18, 2005

ELEMENTS FOR IMPROVING THE TEACHING OF THE LATER PHASES OF THE MECHANICAL ENGINEERING DESIGN PROCESS

Damien Motte, Robert Bjärnemo, Per-Erik Andersson

Keywords: embodiment design, detail design, mechanical engineering design education, mechanical engineering design process

1 Introduction

The study reported here focuses on teaching in embodiment design and detail design phases of the mechanical engineering design process, or design process for short. Teaching of the design process is often concentrated on the conceptual design phase, while the later phases are often reduced to a cluster of techniques and guidelines that help in solving specific problems but do not thoroughly guide the designer through the embodiment and detailing phases. From an earlier study [1] it was observed that the differences between experts and students were partly due to the students' less effective design approach. Thus it was decided to implement a detailed design process model for the teaching of the later phases of the design process. This paper assesses whether the introduction of this process increased students' design skills (effectiveness and efficiency).

2 Objectives

Effectiveness and efficiency are two measures that are in the focus of most studies of the design process, though often under different designations. *Effectiveness* refers, in our case, to the capacity of the students to implement the necessary design steps (activities) that should assure a correct design procedure (independently of the final result). *Efficiency* refers to the success in accomplishing the intended purpose, in other words it measures to what degree the students have successfully solved the design problem (independently of the process employed). While generally the latter is emphasized when dealing with design education, both are of equal importance. Indeed, an early assimilated "correct" design process avoids the development of bad habits that are difficult to change and remodel.

Thus the study will first focus on whether the design process taught has been assimilated, that is not only been understood but also applied effectively.

Secondly, it is important to assess the extent to which the process definitely contributes to a more effective design approach (in comparison with using an intuitive design process).

Finally, the capacity of successfully solving a design problem is assessed. A "good" design is the result of many, deeply interwoven factors, like design knowledge, prior experience, creativity… and the design process is just one of them. Thus when measuring the impact of a good design process on the quality of the problem solution, one cannot expect a result free from disturbances, as all other factors cannot be considered equal, even for students. Nevertheless, as embodiment and detail design problems are more well defined, thus more suitable for being described in a more thorough procedure, the possibility of a correlation between process and design result was measured.

3 Background

Though the definitions vary among authors, embodiment design and detail design are presented as the design activities that follow the settings of the functions and the technical specifications of the product-to-be together with its working principle, developed during the conceptual design phase. The first step is then to define the product architecture, which describes the deployment of the function elements into different subsystems and their interaction with each other. This step is generally included in the embodiment design process [2], but not always [3]. This study focuses only on the following steps, which concern the activities from the very embodiment of the subsystems, or parts (that is giving form, shapes and dimensions to the subsystems) up to a detailed level where the part is ready to be produced.

During the teaching of these last design steps, the student is taught to follow a series of *basic rules*, *principles* and *guidelines* that will help him or her through the synthesis activity of embodying the product. The *basic rules* are the common denomination for the notion of *simplicity*, *clarity* and *safety*, which the mechanical design engineer, or designer for short, needs to have in mind during the design activity. The *principles* are well-grounded heuristics based on "best practices" that help the designer towards an effective design (e.g. principle of direct and short force transmission path, principle of self-help). The *guidelines* are procedures to be followed for some specific purposes. They cover the area of design for X. These concepts are described at length in [2], where an extensive compilation of *guidelines* and *principles* can be found. The student also needs to acquire the reflex of checking his or her design against the *factors* that will affect the product during its life cycle. These factors must act as a trigger for the orientation of the design tasks. These factors concern the impact that the part can have on the environment (process, user, environment, quality/standards) during the product life cycle (design, manufacturing, assembly, packaging, transport, storing, use, maintenance, elimination/reuse/recycling) [3]. It can be observed that the set of factors presented in [2] can be retrieved from the study of these two dimensions (product life cycle and product environment).

Several of these methods and techniques are sometimes hard for the student to grasp (e.g. the concept of *clarity*), but the most difficult challenge is to assimilate and integrate all these numerous methods and techniques. Many of the students have difficulty to prioritize and to organize their activities following these rules, guidelines and principles. Even one year after the lecture on embodiment and detail design, students in their last year of study —seniors with a one-year mechanical design project and finishing their masters theses— are still largely under-using basic rules and principles and do not take into consideration many of the external factors [1]. Clearly, the students need to be guided through the processes of embodiment design and detail design.

Nevertheless, the use of hierarchically structured, prescriptive design processes has been questioned during the last decade. Complementary studies showed that experts and students only loosely followed a breadth-first, systematically defined process; they rather adopted an opportunistic top-down approach. Results are contradictory, showing either a relatively positive impact [4] (p. 148, the successful designers use a defined strategy to control the design process) a relatively negative impact [5] (the opportunistic strategy seems to give better results than a hierarchically phase-oriented strategy) or no impact [6] of the process on the product design. These studies, however, mostly concern the early phases of the design process, when the problem is ill defined and creativity is required. Moreover, these studies focus mainly on the impact of using a structured process method on the final design (efficiency). As mentioned above, effectiveness is to be considered as well. Finally, during the embodiment design and detail design phases, the problem is more well defined (and not open-ended). Thus the pertinence of using a structured design approach remains to be studied.

Few processes are described in the literature (e.g. in [2]) providing process or procedure models for the embodiment design and detail design phases. An overview of the different processes is to be found in [1]. The main shortcomings are that the processes presented are very general in nature and are not specifically aimed at the granularity level required for, and at the concreteness requested by, the students. Thus a specific process, based on [3], has been developed in order to guide the students through the embodiment design and detail design processes. This process is presented and discussed in the next section.

The present study focuses mainly on the synthesis activity of embodiment design and detail design. The analysis part consists in the checking, refining and optimizing of the design solution; thus analysis comes after synthesis. A method specifically developed for the integration of the analysis tools in the design process can be found in [7].

4 The embodiment design and detail design process

The different constitutive elements of the design process that have been presented to the students and used as a basis for this study are discussed in the first part of this section. The second part presents the process.

4.1 Discussion on the design process taught

The process taught to the students is based on Olsson's systematic design process [3], specifically the process part dedicated to the embodiment design and detail design phases. The product architecture in this process is considered separately, upstream from the embodiment design and detail design phases, and consequently this process corresponded to our needs. The process steps are based on a general creative problem-solving process (problem understanding, solution generation, solution evaluation), which is considered to be a representative model of the design activity.

The elements added to the initial process have been extracted from the former observations of juniors, seniors and experts while solving a design process task. The design processes have been compared between students and experts, and between juniors and seniors. The juniors were the students who had not attended the embodiment design and detail design lectures, whereas the seniors were about to graduate. Comparisons of the design activities were performed at different granularity levels: at the strategic, tactical and operational level respectively. Moreover, the use of the basic rules, principles and guidelines and references to external factors was observed. The results of this in-depth study are presented in [1] (strategies and tactics) and [8] (design operations, modeled as a problem-solving process). The main results that are of relevance for this paper are presented in Table 1. In this table, the design process elements performed by the experts serve as models; the elements that are not performed by the juniors or seniors are mentioned under their respective categories. The negative design process elements performed by the three types of designers lie under the "weaknesses" categories.

Table 1. Differences in strategies, tactics and design operations between juniors, seniors and experts (from [1] and [8]).

Strategies	***Tactics***	***Design operations***
Experts: General Strategy: Rapid understanding of the problem. Considering, very early in the process, the shape of the parts and their interactions. Concrete choice of materials. Optimized choice of standard components. Dimensioning of the joints. Variations: Dimensioning by experience or by mechanical analysis. Often depth-first strategy. Clear method that is loosely followed.	*Experts:* Think in terms of standard components. Think in terms of concrete shapes. Document the work. Detail drawing. Use of basic rules. Criteria: Minimize costs. Avoid unique parts. Take production into account. Wait until late before using principles and guidelines.	The design operations were amazingly similar between experts, seniors and juniors: Problem understanding: Did not ask beyond the assignment. Solution development: Interplay between the synthesis activity, mechanical modeling and dimensioning, in this very order. Evaluation operations: - implicit or explicit criteria (one criterion at a time). - roles of the evaluation: decision, reinforcement, judgment, check (control), comparison of solutions.
Students: Seniors: Follow roughly the same process, but considered late in the process, the shape of the parts and their interactions, which led to geometrical problems. Dimensioning by mechanical analysis. Juniors: Do not follow any determined process. Do not prioritize any activity. Avoid dimensioning.	*Students:* Seniors: Do not document the work. Do not use detail drawing. Postpone product concretization. Do not avoid unique parts. Juniors: Do not set any criteria. Adhocism ("I cannot solve this problem, so this is not my problem")	The experts had more evaluation episodes, with more differentiated criteria. The students spent more time on the mechanical analysis due to lack of experience and poorer use of the simplicity and clarity rules.
Weaknesses: Do not plan design activity. Do not use a developed objective function.	*Weaknesses:* No check for other factors than "costs" and "manufacturing / assembly". (Students: seldom check their design.)	*Weaknesses:* Developed only one or two solutions. Check activity considered as secondary. Basic rules often followed only at the beginning of the design process.

From all these elements, the ones that the in-depth study pointed out as the most important in terms of effectiveness and efficiency were included in Olsson's process. These were early concrete choice of material, thinking in terms of standard components, early proportional sketches, continuous documentation, and continuous check for external factors, early consideration of the shape of the parts and their interactions.

4.2 The embodiment design and detail design process

The product working principle and the product architecture are presumed available. Figure 1 presents the overall embodiment design and detail design process. From the product architecture draft, or product layout, the product is to be decomposed into standard components and unique parts that are then selected and developed. The purpose of the product assembly step is to check the assembled product architecture and to provide documentation for the product prototype (detailed drawings, bills of material, etc.). The product is then refined up to the point of manufacture.

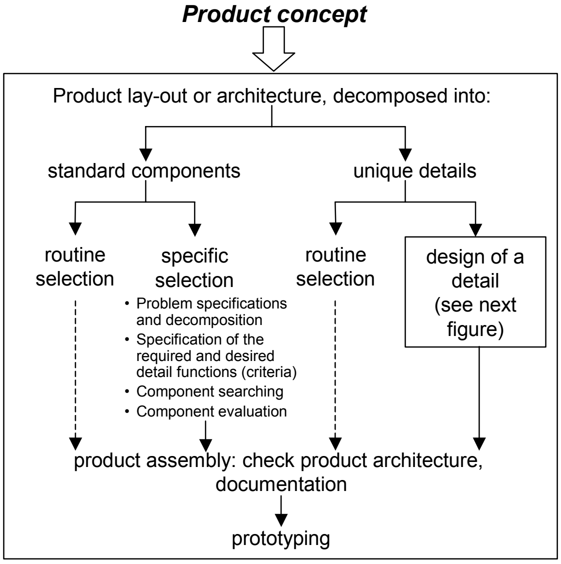

Figure 1. Model for embodiment design and detail design process.

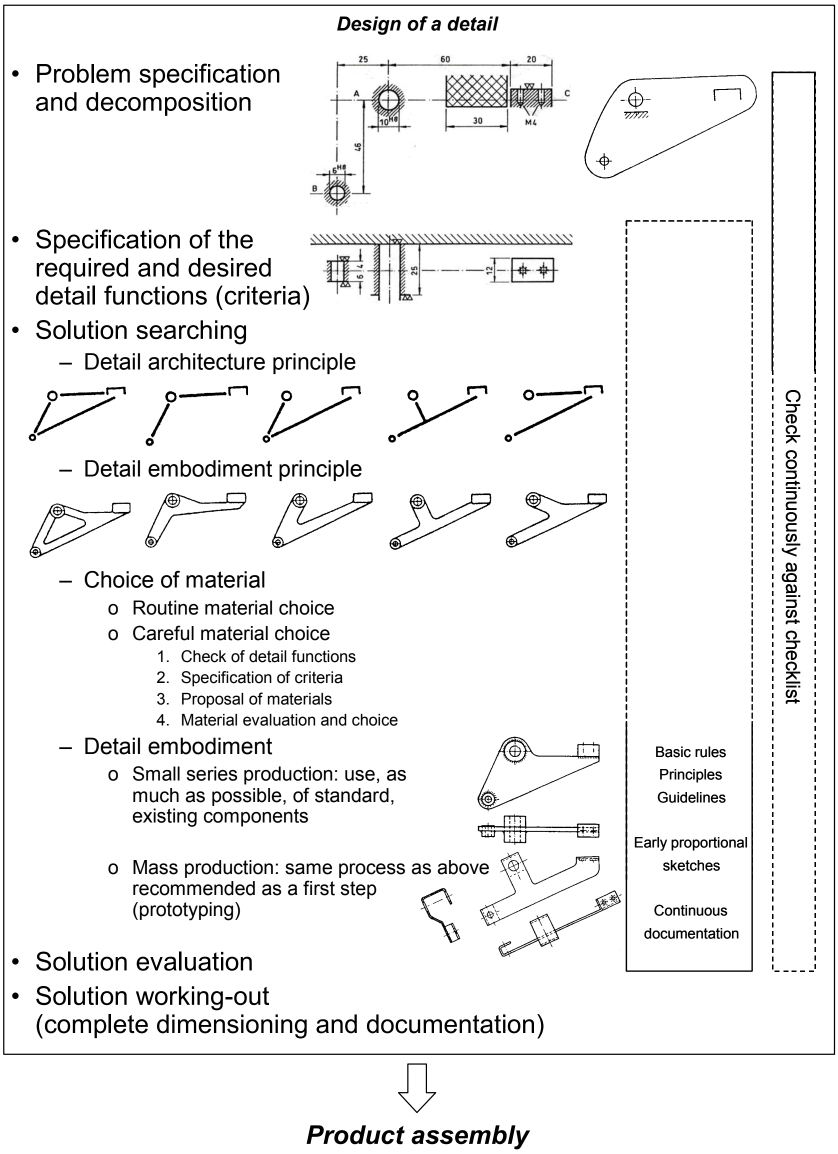

Figure 2. Model of design process of one product detail.

Figure 2 also presents the model of the design process of the unique parts. During the first step, the designer is enjoined to take the time to fully understand the problem. This was a weakness observed in both the experts and the students, though the students had just gone through a conceptual design course. Then the emphasis is put on the specification of the required and desired functions (in terms of criteria). It had been observed that neither the experts nor the students devoted any time to the specification of criteria; experts nevertheless used implicit criteria developed through experience. The criteria are developed from the factors that will affect the product during its life cycle (see section 3). As the overall process presented in Figure 1 is relatively straightforward, the study merely focuses on the model of the design process of the unique parts.

The third step, solution searching, is divided into detail architecture principle, detail embodiment principle, choice of material, and detail embodiment. The simplicity of developing alternatives at the detail architecture principle level should trigger the student in this direction. The detail embodiment principle is meant to force the student to consider the geometrical limitations of the problem. The choice of material is mentioned at length for the same kind of reason: the material constrains the dimensions and the shape of the detail. The detail embodiment step is the step where the student needs to use extensively the *basic rules*, *guidelines* and *principles* that are the core of the embodiment design and detail design lecture. A last rule of thumb was added for this step: the experts reasoned in terms of standard components (standard beams, etc.) and tended to avoid unique parts as much as possible. When a unique part was needed, it was embodied with consideration to optimal manufacturing time. This seemed to be both effective in terms of analysis time and efficient in terms of design result, and was thus taught to the students. This was even emphasized for mass-produced devices: according to Olsson [3], the same process is recommended, as a prototype is likely to be produced as a first step.

During the fourth step, solution evaluation, the student has to evaluate the developed alternative against the criteria specified in step 2. The last step is the complete dimensioning of the chosen solution. A first calculation of the critical dimensions is necessary during the detail embodiment step, but all complementary, often standard, calculations are made for the chosen component.

5 Methodology

The evolution of the students' design skills (effectiveness and efficiency) was studied by means of a combined assessment of a student examination project reports review and the analysis of a similar design task performed under experimental conditions. This analysis was performed with the help of the verbal protocol analysis method. These two different types of data sources permit a complementary analysis of a design task. They are presented in the first parts of this section. The method of analysis of the reports review is presented in the last part of this section.

5.1 The examination project reports review

Following the set of lectures on embodiment design and detail design where the students learnt how to use basic rules, guidelines and principles as well as the design process presented in the previous section, the students were given a design assignment to perform so as to validate this part of the course. The work quantity needed for this project corresponds to a full man-week. The assignment is presented in Figure 3. The students were explicitly asked to follow the different steps of the design process, and to report their results, which meant to briefly report the outputs of each step.

The study of project reports introduces a bias in the study of the design process because 1) the report is written afterwards and thus it cannot be insured that it reflects the effective design activity, and 2) the report is written in a way that fits the proofreader's requests. As students were asked to follow the prescribed design process, there is no doubt that many reports have been arranged to show that this request has been fulfilled (note that the design process itself did not count for the examination assessment, relieving the students from feeling constrained to actually follow the prescribed process). Nevertheless, it is relatively easy, reading each report, to determine whether the student really understood the steps reported. Moreover, as the system to design was to be fully dimensioned, the necessary amount of work may have played the role of a trigger for the students to organize their work, and thus to be inspired. Finally, a significant number of the students did not, despite all, try to include in their reports the design steps they did not follow. Indeed almost no design process reported is complete, which can allow us to make the hypothesis that the steps reported were effectively followed. The sequencing of the design activities is studied with the experimental study.

5.2 The experiments

The verbal protocol analysis has been extensively used during the past decade for the study of design activities. This method had been showed to be powerful for explorative studies of the design process at a very fine level of observation. The verbal protocol analysis consists in the analysis of the verbal transcription of a recorded participant invited to think aloud while performing a task. The protocol is then cut into single episodes representing a specific activity, a set of activities, or coding scheme being used a reading grid. The analysis of this sequence of single activities permits extracting patterns of behavior or special characteristics about the process studied [9].

For this particular study, three sets of two experiments were considered. Two students participated in an experiment prior to the beginning of the embodiment design and detail design lectures. The design assignment is presented in Figure 4. Once the lectures ended and reports were delivered, a second set of experiments took place. One of the two students repeated the same type of experiment with another assignment (see Figure 5), while a third student performed the design assignment of the first set of experiments. This permitted following more carefully the evolution of one student and to account for the evolution of the others. The last set of experiments was carried out in a former study: two senior students took part in the same type of experiments under the same conditions (the design assignment is presented Figure 4). This permits comparing the progression of the students' effectiveness with students who did not learn any structured embodiment design and detail design process.

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. Afterwards, there was a short interview in which the subjects were asked to evaluate their design and the experiment. The student who took part in two sets of experiments is hereafter called S2, the student who participated in the first set is called S1 and the one who participated in the second, S3. The senior students are called Ss1 and Ss2.

Examination project assignment:

"Two beams are loaded with forces F1 and F2 (see opposite figure). The beams have to be bolted together by means of a support on the wall. The beams end up the one with a male thread, the other with a fork.
In order to have small deformations, the design needs to be stiff. Moreover the weight should be low. The support will be bolted onto the wall. Due to lack of space, it is only possible to fix the support to the vertical wall within a defined interval given in the opposite figure.

A sketch of at least two embodiment principles is required. Evaluate the alternatives and select one embodiment. For the chosen embodiment, a drawing with the main dimensions will be presented. The different steps of the design process shall be reported as well."

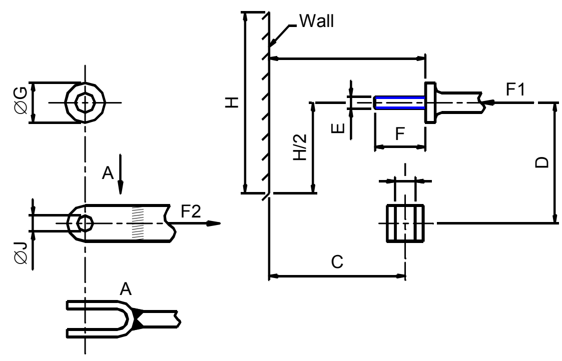

Figure 3. Examination project assignment.

Assignment of the first set of experiments:

"A hydraulic piston has to be fixed by means of a support to the ground. Below the piston an installation lies on the floor (see opposite figure). The support is to stand by the side of this installation.
In order to have small deformations, the design needs to be stiff. Moreover the weight should be low. The piston, guided laterally, takes a force of 90 kN. The piston has a diameter of 100 mm and is to be fixed to the support with fixations. Possible fixations are given in appendix.
The piston is going to be used scarcely, therefore there is no risk for fatigue.
The support will be manufactured in one example.
The support will stay inside in a workshop environment.

The assignment consists in the drawing of an embodiment of the support."

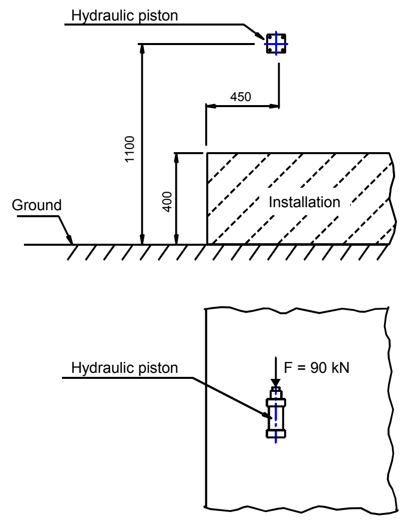

Figure 4. Assignment of the first set of experiments.

Assignment of the second set of experiments:

"The design project consists in the embodiment of a wall-mounted support that fixes both the motor and the pump.
In order to have small deformations, the design needs to be stiff. Moreover the weight should be low.
Due to lack of space, it is only possible to fix the support to the vertical wall within a defined interval given in the opposite figure.
The motor and the pump will be bolted on the support.
The support will be bolted onto the wall.
The moment transmitted between the motor and the pump is 1500 Nm.
Motor weight = pump weight = 200 kg.
The center of gravity of the motor and the pump are represented in the top view.

The assignment consists in the drawing of an embodiment of the support."

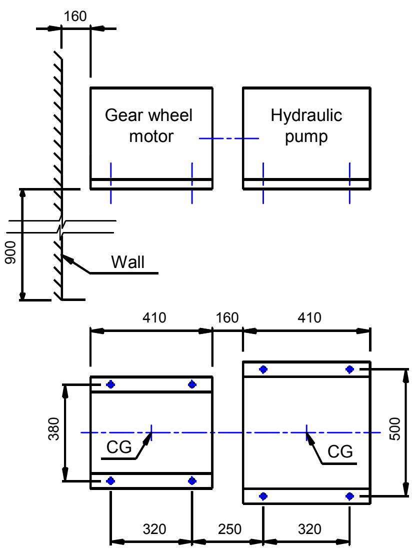

Figure 5. Assignment of the second set of experiments.

5.3 Method of analysis

Three different methods were used to answer the questions asked in the objectives section.

Design process assimilation

Each method helps in complementary ways to assess the extent to which the students have assimilated the design process. The project reports give access to design steps that are not possible to explore on a time-limited experimental basis (e.g. solution evaluation and solution working-out). The experiments give an in-depth insight into the realization of some other steps, of which only the final results are available in the students' reports.

The project reports review permits knowing if each process step has been understood: the reported output of each design process step does or does not correspond to the expected one. For each step present in the report, the assimilation level is ranked with the following scale: -1: not understood, 0: understood (used correctly), 1: assimilated (understood and used in an autonomous way). For the assessment of the whole process (see Figure 2), the solution searching process was treated separately. The process was considered understood if 3 of the 4 steps of the solution searching process had to be reported and understood as well as 3 of the 4 remaining steps (Problem specification and decomposition, Specification of the criteria, Solution evaluation, Solution working-out). For the students whose process was considered understood, the assimilation was measured by the sum of the assimilated steps, referred to the number of steps reported.

Then the protocol analyses of the first and second set of experiments were compared. The first set served as a control set. The study of the second set was used 1) to confirm whether the students' design process derived from the process taught or was the fruit of prior experience; 2) to study more specifically some steps for which the study of the project reports was questionable (the problem specification and decomposition step, among others); 3) to examine whether there was a correspondence between the results of the projects review and the verbal protocol study. The coding scheme presented in [1] was used for this purpose.

Increase of effectiveness

The second and third sets of experiments were used for this analysis. This year's students were compared with last years' students who did not learn any structured embodiment design and detail design process. The part of the design process in the students' increase of effectiveness was assessed by investigating to what extent they avoided the weaknesses observed at the level of design strategies, tactics and operations observed earlier (see Table 1). The coding schemes used for this study are reported and discussed at length in [1] and [8], which account for the design strategies and tactics [1] and the design operations [8] respectively.

Measure of efficiency

The project reports link the design results (the final product) to the design process and thus permit an answer to the third question of the objectives, concerning the impact of the design process on the students' efficiency. The quality of the results was measured by two factors: 1) correspondence between the criteria and the chosen solution (that is, if the chosen solution is the best one in relation to the criteria set by the student; 2) the accuracy of the dimensioning calculations (in other words, if the designed support will hold!). The quality of the process was measured the same way as presented above (in the process assimilation part). A "good" design process reflects the correct use of the process. A binomial analysis was carried out to determine whether the null hypothesis "the number of pairs 'good design/good design process' is only due to chance" could be rejected.

6 Results and discussion

6.1 Design process assimilation

The assessment of the students' assimilation of the different steps of the embodiment design and detail design process is presented in Table 2. Each process step, and then the whole, are analyzed in the light of both the design project report review and the verbal protocol analysis.

From the design projects review, the conclusion was that the problem specification and decomposition step has been considered as understood by the student, but almost none tried to investigate beyond a simple analysis of the assignment. Amazingly, the results of the experiments show on the contrary an extensive examination of the design problem and a thorough decomposition into sub-problems. Students S2 and S3 did not spend more time than was observed in the first set of experiments, but they did concentrate on the first step at the beginning of the experiment, rather than coming back to it later on. During the first set of experiments, S2 and S1 needed from time to time to come back to the problem-understanding step; they did not try to decompose the problem. During the feedback interview, S2 and S3 evoked the problem decomposition as very useful to organize their work when they were "stuck" somewhere. Beyond the specification and decomposition, S2 and S3 also planned their work, which was not observed during the first set of experiments. Thus fewer loops were observed, which demonstrates more effective work.

The high frequency of the specification of criteria step may largely be due to the fact that the solution selection (based on those criteria) was a part of the project evaluation. Around a third of the students did go beyond the specifications present in the design assignment and took into account some of the factors obtained by studying the impact of the product on its environment (see section 3). S2 explicitly made a list of the desired and required functions (not done during the first set of experiment); S3 did not do it in such an organized way, but reasoned often in terms of desired and required function while prioritizing his work.

Just more than half of the students reported their detail architecture principles. This is certainly due to the fact that they reported their detail embodiment principles. S1, S2 and S3 all developed detail architecture principles. The low average score of 1.19 has little signification here, as the design project report review could not reveal the underlying process. The experiments seem to show that the students already use this before this course, although more at a representational level than as a way to generate different solutions.

The scores of the number of students that understood and those that assimilated the detail embodiment principle are even. What differentiates them is that some students took care of the interface problems (fixations to the wall, to the beams, see Figure 3) already at this stage, thus avoiding developing uselessly impossible details. Is this step really understood, or is the good score due to the fact that the report is written afterwards? The verbal protocol analysis is unfortunately inconclusive here. S2 developed very accurate detail embodiment principle on both sets of experiments, while neither S1 nor S3 did. This cannot confirm or disallow the results of the design project report review.

Table 2. Assessment of the students' design process assimilation.

Process step	*Frequency of the reported step*	*-1: step not understood*	*0: step understood*	*1: step assimilated*	*average*
Problem specification and decomposition	86.67%	0.00%	96.15%	3.85%	1.04
Specification of criteria	96.67%	3.33%	66.67%	30.00%	1.27
Solution searching					
Detail architecture principle	56.67%	5.88%	76.47%	17.65%	1.12
Detail embodiment principle	96.67%	10.34%	44.83%	44.83%	1.34
Choice of material	90.00%	3.70%	62.96%	33.33%	1.30
Detail embodiment	96.67%	37.93%	10.34%	51.72%	1.14
Solution evaluation	93.33%	3.57%	42.86%	53.57%	1.50
Solution working-out	93.33%	0.00%	42.86%	57.14%	1.57
Whole Process	-	26.67%	36.67%	36.67%	1.10

The choice of material was relevant in the reports. The verbal protocol study of the second set of experiments showed a different picture: the material was chosen when needed for calculations, sometimes only during the solution working-out step. The students did not seem to have realized that the material constrains the development of the detail. This must be added to the fact that the students have less practical knowledge: students often ignore the properties and range of use of the different materials at hand.

A large span can be observed in Table 2 at the detail embodiment step. Indeed a large number of the students (38%) completely ignored many of the elements learned during the embodiment design and detail design lectures (which are nevertheless the core of the course), while others employed them nicely (52%). The basic rules were used by everybody and assimilated by half of them, according to the students' explanations in their project reports. Only half of them checked on factors that could affect the design; three quarters of them used some guidelines and principles taught in class in a way that showed that they had understood or assimilated them. An amazingly important number of them did try to think in terms of standard components (85%) successfully (50% understood, 50% assimilated this technique). Nevertheless, if these techniques are considered together, only 60% successfully combined them, and the other 40% did not succeed in seeing the whole picture. The protocol studies showed a small increase in the use of basic rules, guidelines, principles, and checking for other factors, notably for simplicity, but not significantly. S2 checked his design more often than during the first set of experiments. The students never tried actively to use these techniques, and the limited time of the experiments prevented us from confirming the assimilation rate showed by the design project reports review.

The solution evaluation was quite well understood. The verbal protocol study showed that this step was used artificially for the sake of the report: neither S2, who performed a thorough criteria specification step, nor S3 tried to evaluate their solutions in an organized manner. There was no evolution in the number of evaluation episodes (4 evaluations per hour), and the time dedicated to them was still very short (between 5 and 40 sec).

Almost all the students carried out a developed dimensioning of the chosen solution; nevertheless, the majority of them (57%) did not fully dimension the system. The non dimensioned elements were, in these cases, the interfaces (between the technical system and the wall, between the technical system and the beam.) Due to the limited time of the experiment, this step could not be fully observed.

In general, the students have understood the embodiment design and detail design processes, though the 23% of them that did not is still a high rate. The verbal protocol study showed that the students did organize their work much better, and followed a logical sequencing of action. The solution-searching step is an exception to this, being performed in a random way that is not distinguished from the behavior observed in the first set of experiments.

The design project reports review and the verbal protocol study were found to be quite complementary methods, the former showing the results of the design process steps and the latter the way the students performed each step. This analysis showed as well which results could not be confirmed: the study was inconclusive for the detail embodiment principle step and contradictory for the material choice step. A higher number of verbal protocol studies could be a solution for this purpose, but as these dilemma points have been well identified, other kinds of experiments, more particularly focusing on these points, could be considered.

6.2 Increase of effectiveness

The last section showed the students' design process assimilation level, insuring an effectiveness increase. This section considers whether the increase of effectiveness was due to the process taught or to a natural, experience-related increase. For that purpose, the improvements noticed are compared to last year's students' improvement. Last year's students were seniors, which meant that they had more experience than S2 and S3.

No students from last year used the problem decomposition technique. One of the subproblems of S3 was the interface between the piston and the support (see Figure 4), which led him to integrate this constraint very early in the problem. Ss1 created a unique part for this purpose, while Ss2 did not develop a solution for this problem. This step thus largely improved the students' effectiveness.

Neither Ss1 nor Ss2 developed a list of criteria. This was compensated by their experience, meaning finally that the assimilation of the design process compensates partially for experience. This attention to the criteria specification must be tempered by the fact that these criteria were not used for solution evaluation. Solution evaluation is a step that, according to the observations, was always performed solely by experience, be it by the seniors or by the experts.

The senior students did not try to develop more solutions with the help of the detail architecture principle. As the study of the detail embodiment principle was inconclusive, this could not be further studied here. The choice of material made by the seniors relied on their experience. Concerning the detail embodiment step, the seniors showed more control of the basic rules, more confidence in the use of the guidelines and principles, and more experience in checking the design against other factors. This tends to show that increase of effectiveness for these elements is largely due to experiments. S2 and S3 nevertheless tended to think more in terms of standard components and interface during this step than the seniors who postponed these problems. S2 and S3s' solutions were then easier to manufacture. This rule of thumb seems then to be significantly important for this step.

Finally, S2 and S3 organized their work better than did Ss1 and Ss2. Ss1 and Ss2 had to come back more often to the problem specification. The seniors nevertheless carried out the solution-searching step more smoothly.

6.3 Contribution to efficiency

Though many other factors play a role during the design process (experience, knowledge, natural skills), a multiple regression analysis was performed to assess if all the elements taught during the embodiment design and detail design process course had a correlation with the design result. These predictors were: a) design process, b) basic rules, c) principles, guidelines and factors, d) number of relevant alternatives, e) use of standard components. Amazingly, the analysis showed a R^2 of 0.40, significant for $p<.05$, meaning that these elements put together explained 43% of the observed results. A stepwise multiple regression analysis was then computed to extract the most important variables. The process itself was not significantly correlated with the quality of the final design. As Figure 6 shows, many design were of good quality while the design process was not followed or understood. The use of standard components predictor emerged as the significant outcome predictor, accounting for 31% of the observed results. This result is nevertheless to be taken with caution, due to the small number of reports studied and the uncertainty linked to the necessary suggestive understanding assessment of the design elements.

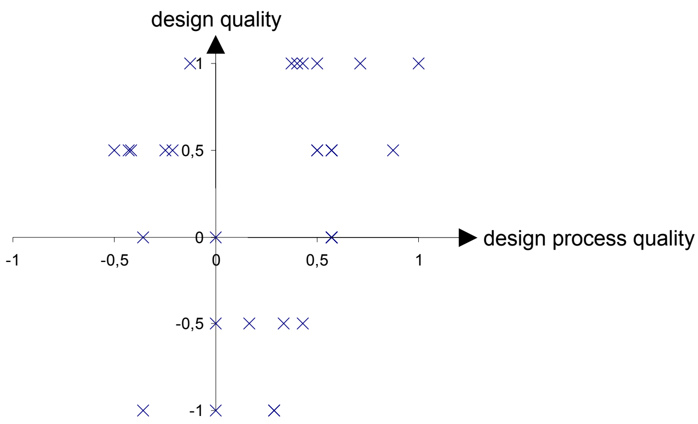

Figure 6. The design quality function of the design process quality

6.4 Reflections on the investigation approach

The design project reports review made it possible to assess the students' assimilation of the process, and the verbal protocol study to confirm or disallow it. The combination of both made it possible to illuminate the needed improvement towards a better teaching of the embodiment design and detail design processes. Some elements were nevertheless inconclusive and contradictory. Other kinds of experiments, much faster and effective than verbal protocol studies, could be considered that would focus on these elements. As such, the combination of both methods is a good technique to sort out the points to focus on.

6.5 The design process presented

Even if the design process taught to the student did not lead to a better design result, the effectiveness of the student increased significantly for some step of the design process. The students organized their work better and avoided useless feedback loops, thus insuring a decrease of design time and, ultimately, costs.

There was no sign of a *decrease* of efficiency due to the process (a very constraining and hard to understand process might have led to that). What is missing, however, is comparison of the quality of the design results obtained without applying a structured design process with results obtained by applying a structured design process. [5] showed that concerning the early embodiment design phase, the students obtained better results with an opportunistic design activity. This point remains inconclusive for the process presented.

The elements of the process whose teaching needs to be improved first are, according to this study: 1) solution searching, 2) solution evaluation. Concerning the solution-searching step, the importance of the material choice must be clarified; the students have to develop more solutions with the help of detail architecture principles. The use and articulation of basic rules, guidelines and principles during the detail embodiment step must receive more attention in the teaching, but more research is needed in this area.

One element that appeared during the feedback interviews of the second set of experiments is that a structured process is actually requested by the students. Independently of the concepts of efficiency and effectiveness, the students acknowledged that they wanted to know where to start designing and which steps to use. The design process is there used as a clue for the students that they refer to when they get stuck during the design activity.

This opens a new perspective on the elaboration of design process models. Apart from focusing on increase of efficiency and effectiveness, design process methods need to focus on the facilitation and simplification of the design activity. A design process method that is as little intrusive as possible, easier to learn and apply, with a great modularity that allows the designer to take the elements he or she needs at diverse moments of the design activity, this is what seems to correspond to the expectation of the students. Moreover these characteristics are compatible with the studies that showed how constraining structured methods led to inferior design results [5]. This could even be generalized to all categories of designers. Many studies showed that professional designers followed a very loosely structured approach to the design activity (e.g. [10]). Such a design process method, focusing not on optimizing design efficiency but optimizing the ease of design, would be used by the designer only when experiencing a problem. Deeper studies should focus on the analyses of such problems as the weaknesses presented Table 1, and the "remedies" being integrated in the design process. The introduction of the heuristic "think in terms of standard components" in order to avoid later geometric and shape-related problems seems to confirm this, as its impact on the design result seems significant.

This latter, mostly unexpected, result from this study is still highly hypothetical, and needs further investigation. But it proposes a link to the span observed between the supporters of a free design activity and the defenders of a hierarchically structured design process.

7 Conclusion

The introduction of a structured embodiment design and detail design process method to the students increased their effectiveness for certain steps of the design activity like problem specification and decomposition, and criteria specification. The students went faster and earlier to more concrete solutions and avoided useless feedback loops. This ensures decrease in terms of time. There is no correlation between the design process observed and the design results, but the heuristic "think in terms of standard components" seems to have an important impact on the results. Beyond the technical assessment of the process, the students themselves appreciated that they could be guided at an operational level during the design activity.

The combined use of design project reports review and verbal protocol study was adapted to the objectives of this study. Nevertheless, some steps should be investigated with deeper, more specific experiments.

Another result of this study that requires further investigation is that the focus on design process should be shifted towards the goal of smoothing the design activity, which in turn may indirectly result in optimizing efficiency and effectiveness.

References

[1] Motte D., Andersson P.-E., Bjärnemo R., “A Study of the Mechanical Designer’s Strategies and Tactics During the Later Phases of the Engineering Design Process”, Proceedings of the DTM/ASME, Salt Lake City, 2004.

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

[3] Olsson F., “Primärkonstruktion” (in Swedish), Lund University, Machine Design Division, 1995.

[4] Dylla N, “Denk- und Handlungsabläufe beim Konstruieren” (in German), Hanser, Munich, 1991.

[5] Bender B., Blessing L.T.M., “On the superiority of opportunistic design Strategies during Early Embodiment Design”, Proceedings of the International Design Conference, 2004.

[6] Mullins C.A., Atman C.J., Shuman L.J., “Freshman Engineers’ Performance When Solving Design Problems”, IEEE Transactions on Education, 42(4), 1999, pp. 281-287.

[7] Eriksson M., Burman Å., “Improving the Design Process by Integrating the Design Analysis”, Proceedings of the 15th International Conference on Engineering Design in Melbourne, 2005 (accepted).

[8] Motte D., Andersson P.-E., Bjärnemo R., “Comparative Study of the Student’s Design Process: Implications for the Teaching of the Later Phases of the Mechanical Engineering Design Process”, Inaugural CDEN Design Conference, Montreal, 2004.

[9] Ericsson K.A., Simon H.A., “Protocol analysis: verbal report as data” (Rev. Ed.), MIT Press, Cambridge, 1993.

[10] Visser W., “More or less following a plan during design: opportunistic deviations in specification”, International Journal of Man-Machine Studies, 33, pp. 247-278.

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
Phone: +46 46 222 85 13
Fax: +46 46 222 80 60
E-mail: damien.motte@mkon.lth.se