Improving design processes through structured reflection: case studies
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Improving Design Processes through Structured Reflection: Case Studies

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Improving Design Processes through Structured Reflection: 
Case Studies

Isabelle M.M.J. Reymen

Abstract
The approach to and results of the empirical study Isabelle Reymen performed at the beginning of her Ph.D. research project is described. The aim of the project was to develop domain-independent descriptive and prescriptive design knowledge. Because the literature did not offer enough information to develop domain-independent design knowledge that is based on several disciplines, she has chosen to get input from the design practice. The empirical study has been performed to explore the design practice and to inventory the most important characteristics of design processes in several disciplines. Design projects of junior and experts designers in the disciplines architecture, software engineering, and mechanical engineering have been studied in the form of case studies. The results of the performed cross-case analysis have been a basis for the development of descriptive design knowledge. Final descriptive results, described in the Ph.D. thesis of Isabelle Reymen, are a design philosophy and a design frame.

The goal of this report is to offer researchers more information about the performed empirical study and its results. The report includes two main parts: the first part concerns the performed case studies; the second part concerns the cross-case analysis that followed the cases studies. The first part includes an explanation of the choice for case studies as a form of empirical research, a description of the case study protocol, and a discussion about the selection of the cases. It also contains summaries of the different cases and a description of the results. The second part describes the approach to and the results of the cross-case analysis. More about the Ph.D. project and its results can be found in the thesis, which is also published as SAI Report 2001/1.

Keywords
Design research ; empirical study / design process ; characteristics / engineering design disciplines
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1 Introduction

This report describes the approach to and results of the empirical study I performed at the beginning of my Ph.D. research project. The aim of the project was to develop domain-independent descriptive and prescriptive design knowledge. Because the literature did not offer enough information to develop domain-independent design knowledge that is based on several disciplines, I have chosen to get input from the design practice. The empirical study has been performed to explore the design practice and to inventory the most important characteristics of design processes in several disciplines. Design projects of junior and experts designers in the disciplines architecture, software engineering, and mechanical engineering have been studied in the form of case studies. The results of the performed cross-case analysis have been a basis for the development of descriptive design knowledge. The resulting descriptive knowledge, described in my Ph.D. thesis, is a design philosophy and a design frame. The design philosophy is a set of concepts and terms for describing a design process in a domain-independent way. The design frame offers a means to structure the description of a design process in a domain-independent way. More about the Ph.D. project and its results can be found in [Reymen, 2001a] or [Reymen, 2001b].

The goal of this report is to offer researchers more information about the performed empirical study and its results. In the report, two main parts can be recognised: Chapters 2, 3, and 4 deal with the performed case studies whereas Chapters 5 and 6 deal with the cross-case analysis that followed the cases studies. The report starts in Chapter 2 with a description of the approach to the case studies. The chapter explains the choice for case studies as a form of empirical research. It also gives a description of the case-study protocol and discusses the selection of the cases. In Chapters 3 and 4, the case studies of the junior and experts designers are discussed in more detail. A detailed description of the protocol (including the documents sent to the designers, the question lists used to perform the interviews, and the transcription schemes used) and summaries of the different cases are given. Chapters 5 and 6 discuss the approach to and the results of the cross-case analysis. The final results of the cross-case analysis are the earlier mentioned design philosophy and design frame. In this report, only the results of a preliminary cross-case analysis, the results of a cross-case analysis in each discipline, and conclusions about the influence of the cross-case analysis on the final results are presented. The report ends in Chapter 7 with conclusions. The report is written in English, but the questions asked to the designers were written in Dutch and are included as such.
2 Approach to the case studies

The goal of this chapter is to offer the reader insight into the approach to the case studies. Section 2.1 motivates the choice for a case-study approach. The case-study protocol followed to perform the case studies is described in Section 2.2. Section 2.3 motivates the selection of the cases.

2.1 Motivation of the case-study approach

To find general characteristics of design processes in several design disciplines in practice, at the beginning of my project, qualitative empirical research seemed most appropriate and was chosen as a general form of research. Case-study research is a specific form of qualitative empirical research. To explain my choice, I recall two definitions from the literature. The first one is found in [Yin, 1994]. “A case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident.” The second one is a translation of the definition given by [Wester, 1991]. “A case-study approach is an inquiry of one or more cases going into depth by putting central the complex relations in which the case functions.” Design processes are contemporary phenomena with complex relations between different aspects and many interactions with their context. Hence, case studies are well suited for investigating design processes in practice. The case-study approach, its characteristics, and its types are further described in [Yin, 1994], [Wester, 1991], and [Verschueren et al., 1995].

As sources of case-study information, I have chosen for interviews with designers and for analyses of design-project documentation that was made by each of these designers. With interviews performed at the end of a design project, I could get insight into a complete design process and its context: I could get an integral picture of the design project. The second source of information, namely the project documentation, was used to corroborate the information of the interviews.

I preferred the case-study approach over the widely used method of protocol studies in design research. Protocol studies are performed in laboratory conditions, cover often only part of a design project, and offer thus only information about the design activities performed in the experiment. I was interested in a complete design project and not in detailed information about design activities during short periods in time. In my interviews, I could ask designers to look back on the complete design process and on the design context. An advantage of case studies was also that less pre-structuring was necessary than for performing an experiment using the method of protocol studies; at the beginning of my research project, I had not yet that many ideas about important (domain-independent) characteristics of design processes. For a description of protocol studies, see the special issue of Design Studies [Dorst, 1995].

2.2 Case-study protocol

The course of one case study is described in the case-study protocol. This is a document that contains all procedures and general rules that are followed to execute one case. It can be seen as a script or scenario to be followed. This instrument increased reliability and continuity between cases, and guided me in carrying out the case studies. The importance and design of a protocol is described in [Yin, 1994]. My case-study protocol includes a description of the following main activities: preparing and executing a first interview (about one of the design projects of the designers), processing data of the first interview (transcription), analysing the documentation received from the designer (documentation about one of their design projects), making a summary, preparing and executing a second interview, processing data of the second interview and correction of the summary, and making a summary report of the case. The protocol is first performed for junior and then for expert designers. After the cases with junior designers, a summary of characteristics of design processes in each discipline was made.
based on a brief cross-case analysis of the junior cases and on the literature I studied. Then, the choice for the expert designers was made and these cases were performed. Finally, a real cross-case analysis was executed. Below, the case-study protocol is described in more detail. The approach to the cross-case analysis can be found in Chapter 5.

In the interviews of one hour and a half, open questions about the complete design project were asked. The interviews were tape-recorded and, for each case, written notes were made in Dutch. The first interview was prepared by the designer and by myself. I sent to the designer documents including a personal introduction, a description of the research project, a description of the course of the case study, and a description of how to prepare the interview. The designers provided some facts about themselves by completing a special form and they gathered documentation of their chosen project. I developed a question list to inventory the important aspects of design processes. This list was based on a preliminary version of the design frame (more about the development of the design frame can be found in Section 2.8 in [Reymen, 2001a]). Because I unavoidably made my own interpretation of the answers to the questions of the interview and the contents of the documents, I asked the designers to check my description of their answers and to correct my view. This was done in a second interview or by mail (based on an extended summary of the first interview I sent them).

The raw data (the notes of the first and second interviews and the analysis of the documents) were structured using a transcription scheme (a classification system). The use of this transcription scheme, based on a preliminary version of my design frame, was necessary for comparing the different cases in a cross-case analysis. The transcription scheme included the fields of attention of the first interview. Fields of attention in the first interview with the junior designers were the product being designed, the design process, bottlenecks in the design process, and things learned from the project. A new question list was made for the expert designers. Fields of attention in the first interview with the expert designers were the product being designed, the design process, management of the design process, and things learned from the project. The expert designers were also asked to give feedback on the summary I made about characteristics of design processes in their design disciplines and to give their opinion on similarities between designing in their disciplines and other disciplines. The summary report of each case included a summary of the interviews (in Dutch), a summary of the documentation, the question lists, the transcription, and the transcription scheme.

Two pilot case studies were executed to test a preliminary version of the case-study protocol (including the question lists for the interviews) and to make a time planning for the next cases. One designer from the Faculty of Mathematics and Computing Science and one from the Faculty of Mechanical Engineering of the TU/e, performing a Ph.D. on design, were interviewed, following the preliminary protocol. Afterwards, the interviews were evaluated on contents and procedure and the question list and protocol were improved. After that, twelve more designers were interviewed.

The lists of questions for the interviews and the transcription scheme are related to the research questions of the Ph.D. project as follows. In [Yin, 1994], the following five levels with (lists of) questions are defined. Level 1 includes questions asked to the interviewees; level 2 includes questions for the analysis of one individual case (a transcription scheme); level 3 includes questions for the analysis across multiple cases; level 4 includes questions for the entire project (research questions), calling on information beyond the multiple cases and including literature that may have been reviewed; and finally, level 5 includes normative questions that go beyond the narrow scope of the project. Questions on a lower level must be derived from questions on a higher level; for example, the questions for a cross-case analysis must be derived from the research questions. By making the question levels explicit, a chain of evidence can be established: Questions asked to the interviewees may be linked to the research questions through the questions on the levels 2 an 3; the transcription scheme may be linked to the research questions through the questions on level 3.

The first four levels of Yin were used during my Ph.D. project. The first level contains the questions asked to the interviewees. The questions of this level are divided into two question lists: one general list for the first interview and one more specific for the second interview of each case. Level 2 contains questions for the analysis of one individual case. On this level, the data of the interviews is transcribed into a transcription scheme. The questions on level 3, i.e., the questions for the analysis
across multiple cases (see Chapter 5), are derived from the research questions on the fourth level. The research questions concern the description and support of design processes in a domain-independent way. These had to be answered by synthesising the results of the cross-case analysis and a literature study, concerning general design literature and literature about designing in several design disciplines.

A detailed description of the protocol for the junior and expert designers, including the documents sent to the designers, the question lists used to perform the interviews, and the transcription schemes used, can be found in Chapters 3 and 4.

### 2.3 Selection of the cases

The selection of the cases for the empirical study was inspired by replication logic [Yin, 1994]. This means that every case served a specific purpose within the overall scope of inquiry; this is called the logic of theoretical sampling. Theoretical sampling is opposed to statistical random sampling. Statistical random sampling follows sampling logic [Yin, 1994]; the cases are sample units. For statistical random sampling, a higher number of cases is necessary than for theoretical sampling. Within replication logic, two types of replications are distinguished. For literal replication, cases deviate minimally and are expected to predict similar results; for theoretical replication, cases deviate maximally and are expected to produce contrasting results, but for predictable reasons. In the study, I chose for literal replication within one discipline, whereas I chose for theoretical replication between disciplines. Table 2.2 illustrates the selection of the cases.

<table>
<thead>
<tr>
<th>THEORETICAL SAMPLING</th>
<th>STATISTICAL RANDOM SAMPLING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Every case serves a specific purpose</td>
<td>Cases are sample units</td>
</tr>
<tr>
<td>Few cases</td>
<td>Many cases</td>
</tr>
<tr>
<td>Replication logic</td>
<td>Sampling logic</td>
</tr>
<tr>
<td>Literal replication</td>
<td>Theoretical replication</td>
</tr>
<tr>
<td>Within a discipline</td>
<td>Between disciplines</td>
</tr>
<tr>
<td>Minimal deviation</td>
<td>Maximal deviation</td>
</tr>
<tr>
<td>Predict similar results</td>
<td>Produce contrasting results</td>
</tr>
</tbody>
</table>

Table 2.2: Selection of cases following replication logic.

I was interested in common characteristics of design processes in several design disciplines. I chose to analyse the design process of individual junior and expert designers at the end of their design project in three disciplines. The choice for individual designers was made to limit the scope of the research. Furthermore, I assumed that, at the end of a design project, designers have a good overview of the design project (but may also have already forgotten certain aspects). The combination of junior and expert designers was chosen to get a good overview of important aspects of design processes: I assumed that for expert designers, many aspects of a design process are already part of their implicit knowledge. Junior designers just learned how it is to design during a real design process. Thus, I expected that junior designers experienced certain aspects explicitly, whereas those aspects would already be implicit for expert designers and vice versa. Summarising, the cases were chosen to differ from each other with respect to the experience of the designer and the product being designed. Together, the junior and expert cases covered a wide range of design projects.

Twelve case studies were performed, four in every discipline: two junior and two expert designers\(^1\). A first source of cases was found in the design projects carried out at TU/e. The interviewees were junior designers who had just finished their first large design project. This could be the final project to get their Master’s degree, the final project of one of the design programmes of the SAI, or a Ph.D. design project. Professionals in industry (in the Eindhoven Region) formed a second source of cases. The professionals were chosen for their expertise in their design discipline and their amount of design experience (between 10 and 20 years). Their design projects were more complex than those of the professionals. Two more cases with expert designers, one in the discipline of computer science and one in the discipline of mechanical engineering, were performed to get a broader scope of projects in these disciplines. This was decided after six cases with expert designers were performed.

\(^{1}\)Two more cases with expert designers, one in the discipline of computer science and one in the discipline of mechanical engineering, were performed to get a broader scope of projects in these disciplines. This was decided after six cases with expert designers were performed.
junior designers’ and these projects were executed by more than one person. Since most of the expert designers fulfilled the role of design-team leader, they had a good overview of all the important aspects of the project. The designers that participated in the case studies are listed in Table 2.3.

<table>
<thead>
<tr>
<th>DISCIPLINE</th>
<th>NR. CASE</th>
<th>EXPERIENCE</th>
<th>NAME</th>
<th>DESIGN FIELD</th>
</tr>
</thead>
<tbody>
<tr>
<td>mechanical eng.</td>
<td>pilot-case 1</td>
<td>junior: Ph.D.</td>
<td>D. de Vries</td>
<td>computational mechanics</td>
</tr>
<tr>
<td>computer science</td>
<td>pilot-case 2</td>
<td>junior: Ph.D.</td>
<td>E. Hautus</td>
<td>software engineering</td>
</tr>
<tr>
<td>computer science</td>
<td>case 1</td>
<td>junior: Ph.D.</td>
<td>E. Hautus</td>
<td>software engineering</td>
</tr>
<tr>
<td>case 2</td>
<td>junior</td>
<td>P. de Crom</td>
<td>software engineering</td>
<td></td>
</tr>
<tr>
<td>case 3</td>
<td>junior: Ph.D.</td>
<td>D. de Vries</td>
<td>computational mechanics</td>
<td></td>
</tr>
<tr>
<td>case 4</td>
<td>junior: Ph.D.</td>
<td>M. Renkens</td>
<td>mechatronics</td>
<td></td>
</tr>
<tr>
<td>case 5</td>
<td>junior</td>
<td>J. Bierman</td>
<td>archiprix</td>
<td></td>
</tr>
<tr>
<td>case 6</td>
<td>junior</td>
<td>C. Arts</td>
<td>archiprix</td>
<td></td>
</tr>
<tr>
<td>mechanical eng.</td>
<td>case 7</td>
<td>expert</td>
<td>K. Verhulst</td>
<td>Philips Medical Systems</td>
</tr>
<tr>
<td>computer science</td>
<td>case 8</td>
<td>expert</td>
<td>A. Dobbelaar</td>
<td>Philips Design</td>
</tr>
<tr>
<td>case 9</td>
<td>expert</td>
<td>W. van der Sanden</td>
<td>Philips CFT</td>
<td></td>
</tr>
<tr>
<td>case 10</td>
<td>expert</td>
<td>M. Koster</td>
<td>TU/e</td>
<td></td>
</tr>
<tr>
<td>case 11</td>
<td>expert</td>
<td>P. Sanders</td>
<td>Daf</td>
<td></td>
</tr>
<tr>
<td>case 12</td>
<td>expert</td>
<td>J. Kruithof</td>
<td>XX Architects (former Jan Brouwer Associates)</td>
<td></td>
</tr>
<tr>
<td>case 13</td>
<td>expert</td>
<td>M. van der Palen</td>
<td>Mecanoo</td>
<td></td>
</tr>
<tr>
<td>case 14</td>
<td>expert</td>
<td>J. Brouwer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>case 15</td>
<td>expert</td>
<td>H. Döll</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.3: The designers that participated in the case studies.
3 Case studies of the junior designers

The goal of this chapter is to offer detailed information about the case studies of the junior designers. Section 3.1 describes the protocol used to perform the case studies. Section 3.2 summarises the six cases of the junior designers.

3.1 Detailed protocol

The case-study protocol describes the course of one case, like a script or scenario to be followed. One case study includes two interviews (one general and one more specific). These interviews have to be prepared, performed, processed (transcribed to a transcription scheme), and summarised in a report. Also, a study of the documents offered by the designer must be made. The question lists for the interviews are situated on level 1, the transcription scheme on level 2. Below, each of the activities of the protocol is documented.

3.1.1 Preparation of the first interview

My preparation of the first interview consisted, first of all, of sending introductory documentation (see Table 3.1) to the selected designer. The designer was asked to prepare himself/herself for the first interview by filling out the form depicted in Table 3.2. I prepared me for the specific case by studying the documents the designer already gave me, like a project proposal or (a preliminary version of) the design report. Furthermore, I had to:

− make field appointments and arrange the travel (time and availability appropriate to the interviewee);
− fit the time schema for the interview;
− anticipate on events like changes in the availability of the interviewee, changes in the mood and motivation of the researcher;
− read the most important topics for doing interviews;
− prepare the tape-recorder (tape, volume);
− print out the first interview;
− put ready: pencils, paper, tape-recorder, and all necessary documents (my research document, an overview of the literature, the protocol, the course of one interview, an introduction to the designer, and the general question list).

<table>
<thead>
<tr>
<th>1. personal introduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isabelle Reymen</td>
</tr>
<tr>
<td>civil engineer, architect (KULeuven, Belgium, 1996)</td>
</tr>
<tr>
<td>Ph.D. student since September 1996</td>
</tr>
<tr>
<td>address : TUE, H.G. 6.46, PO Box 513, 5600 MB Eindhoven</td>
</tr>
<tr>
<td>telephone : 040/247 2749</td>
</tr>
<tr>
<td>e-mail : <a href="mailto:isabelle@win.tue.nl">isabelle@win.tue.nl</a></td>
</tr>
<tr>
<td>home-page : <a href="http://www.win.tue.nl/win/cs/tt/isabelle">http://www.win.tue.nl/win/cs/tt/isabelle</a></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. description of research project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Towards a multi-disciplinary framework for design</td>
</tr>
<tr>
<td>Stan Ackermans Institute, Eindhoven University of Technology</td>
</tr>
</tbody>
</table>

prof.dr.dipl.ing. D.K. Hammer (computer science) |
prof.dr.ir. M.F.Th. Bax (architecture) |
prof.dr.ir. J.E. van Aken (management science) |
prof.dr.ir. P. Kroes (philosophy) |
The main purpose of this project is to generate a multidisciplinary framework for design, by looking at the practice of different design disciplines and at the existing design theory. The relevant aspects, generic methods, and problems important for the design route in practice will be inventoried and compared for similarities and differences. A framework will gradually be developed through empirical research by a series of case studies, and through literature study. Specifics will be analysed and an application for the practice will be made. The chosen disciplines are computer science, mechanical engineering and building engineering.

3. Description of the course of a case-study

Every case study will consist of two interviews. You are asked to make a short preparation:

1. for the first interview: fill in a document with some facts and collect some documentation about the design project (discussed more in detail below)
2. for the second interview: write down ideas and comments which come to you after the first interview, and which can be interesting for me

1. The goal of the first interview is to get a broad overview of the project and the design process, following a general question list. This interview will take one hour and a half. Afterwards, a summary of the interview and a reconstruction of the design route will be made by me.
2. The received documents will be analysed to make a description of development of the product.
3. In the second interview, we will discuss some topics more in detail by a specific question list, made after the first interview. Also the analysis of the interview and documents will be checked. Ideas and comments of you in relation to the first interview will be discussed.

Table 3.1: Introductory documentation sent to the designer.

| a) Facts to be filled in personal data |
| name | |
| title | |
| address | |
| telephone | |
| e-mail | |
| education: |
| first program | |
| end project | |
| university | |
| learned about designing during education: |
| extra-curricular activities important for designing: |
| extra education about designing | |
| already executed design projects: |
| others: |
| Ph.D. project |
| title | |
| design course | |
| faculty | |
| department | |
| section | |
| professor | |
| accompany | |
| learned about designing during post-graduate: |
| interesting design literature: |

| b) Documentation |
| Document at least 3 (representative) stages in the development of your project’s product (including first and final stage). Possible documents: |
| project description (specifications) |
| product description |
| process description |
| evaluation of product and process |
3.1.2 First interview

The goal of the first interview was to get a broad overview of the project, following a general question list. The first interview was planned to take one hour and a half. In Table 3.3, the question list used for the first interview is presented. Fields of attention in the first interview with the junior designers were the product being designed, the design process, bottlenecks in the design process, and things learned from the project. The structure of the question list is made in English; the questions are formulated in Dutch, because all interviewees were Dutch. Some questions are also accompanied by possible answers to initiate discussion when necessary and to give an indication of what is meant by the different terms used in the question list.

INTRODUCTION
1. questions, remarks about research project, case studies, other
2. agreement on duration of interview (1.5h)
3. appointment for the second interview
4. questioning difficulties with audio-recording

QUESTIONS

Situation
Welke ervaring heb je met ontwerpen?
Situeer je project in je discipline en omgeving. (representatief)
Wat is het doel van het project? (motivatie)

Product
Hoe heb je het product beschreven tijdens het hele project (vanaf de requirements)? Hoe zou je nu het product beschrijven tijdens zijn levenscyclus?
Welke product-aspecten zijn belangrijk?
(documentatie van ontwerpbeslissingen, specificaties, product decomposition,…)
Welke ontwerdpdilemma’s ben je tegenkomen? Hoe werden ze opgelost?
Welk zijn de belangrijkste transformatiestappen van het product, en hoe worden ze gerealiseerd? (kennis, technologie)
Welke middelen staan ter beschikking tijdens de levensfasen van het product? (grondstoffen, computercapaciteit)
Welke partijen zijn belangrijk voor het product, na het ontwerpproces? (fabricatie, context gebruikers)

Process
Hoe definieer je ontwerpen?
Welk beeld had je vooraf van het ontwerpproces? Hoe zou je het proces nu beschrijven? (structuur, stadia, fasen, toestanden van proces en product)
Werd er gewerkt volgens een voorbeeld?
(theorie, strategie, methode, model, case, conventie, bedrijfscultuur)
Welk waren andere beschikbare hulpmiddelen en welke werden gebruikt tijdens het ontwerpproject? (techniek, tool; medium)
Welk waren de belangrijkste activiteiten tijdens het ontwerpproces?
(alternatieven genereren, kiezen, beslissen, verantwoorden, evalueren, communiceren, documenteren)
(analyse en synthese)
Wat waren hierbij de belangrijkste kennis- en inspiratiebronnen? Hoe wordt de kennis getransformeerd?
Wat zie je als belangrijke vaardigheden voor het ontwerpen?
Welk waren de verschillende partijen, deelnemers en betrokkenen en welke waren hun standpunten tijdens het project? Waaruit bestond het ontwerpteam?

Hoe definieer je project management?

Welke ‘management’-activiteiten werden uitgevoerd tijdens het project?

Wat waren verstoringen, traumatische elementen van het proces? Hoe werden ze opgelost?

Welke dilemma’s ben je tegengekomen tijdens het ontwerpen van het proces?

Hoe werden ze opgelost?

Hoe werd het proces gedocumenteerd?

Bottlenecks
Welke ontwerpproblemen zouden beter ondersteund kunnen worden?

Learned
Wat heb je geleerd van dit ontwerp? (vaardigheden, kennis, heuristieken)
Wat kan je de volgende keer beter doen? Hoe?
Wat moet zeker niet veranderen?

Other aspects of designing
Geef 3 aspecten die belangrijk zijn voor het ontwerpen, en die nog niet genoemd zijn

CONCLUSION
1. summary of the conversation
2. homework for next interview
3. thanking for co-operation

Table 3.3: Question list for the first interview.

### 3.1.3 Processing data of the first interview and of the documentation

During the first interview, notes were made and a tape recorder was used. To process the data of the first interview, first, the interview notes were completed during listening to the tape. Then, the rough interview notes were summarised in Dutch and a code corresponding with the transcription scheme was given. The transcription scheme evolved during the execution of the cases; the final transcription scheme is presented in Table 3.4. Then, the documents received from the designers were analysed and the relevant information was transcribed to the same scheme. Finally, a summary of the case was made.
3.1.4 Preparation of the second interview

The preparation of the second interview included the same activities as for the first interview, except that a specific question list must be made for the second interview for the specific case. The designer was asked to write down ideas and comments which came to him/her after the first interview and which could be interesting for me.

3.1.5 Second interview

Topics for the second interview concerned questions that remained unanswered after the first interview, questions about the documentation, and specific questions concerning the specific project. Also, the summary of the first interview was checked and ideas and comments of the interviewee in relation to the first interview were discussed. The course of the second interview is given in Table 3.5.

**Introduction**

1. explanation of the goal of the second interview (see above)
2. description of the interview scheme (see conversation)
3. agreement of duration of interview (1.5h)
4. description of the processing of the information of the interview
5. asking for questions, obscurities

**Conversation**

The interview scheme of the conversation depends on the specific case. The general contents of the conversation is as follows:
- control summary of interview one,
- discuss ideas and comments of interviewee,
- ask the questions of the specific question list.

**Conclusion**

1. summary of the conversation
2. thanking for co-operation

Table 3.5: Scheme for the second interview.

3.1.6 Processing data of the second interview

To process the data of the second interview, the same activities as for processing the data of the first interview were performed. The summary of the case and of the documentation have been corrected according to the comments of the designer and new insights.

3.1.7 Summary report of the case

The procedure to make a summary report of each of the cases was the following:
- make a short summary of the contents of the case;
- give an overview of the documentation;
- make a short summary of the procedure of the case;
- make a judgement and evaluation of the case (of the motivation of the interviewee, of the process and product of the project, of the course of the interview);
- include a summary of the interview in Dutch;
- make a list of what's learned with this procedure and what can be approved;
- make a list of things learned from the contents of the case;
- make a summary of the documentation;
- make a document of the transcribed contents of the case;
- add question list 1 and 2.
3.2 Summaries of the cases

In this section, a short summary of each of the six junior cases is given. Each description includes information about the title of the project, the background of the designer and the context of the project, a short description of the project, and an enumeration of the documents that were received from the designer. In the last subsection, the main characteristics of the analysed design process of one junior designer are described in the terminology of the design philosophy, one of the developed descriptive results in the Ph.D. project. This description uses the chosen domain-independent terminology to describe design processes. It is claimed that all cases could be described using this terminology, which evolved out of the transcription scheme.

3.2.1 Case 1 (software engineering)

Development of a motion-analysis system for rehabilitation medicine at the VU Hospital in Amsterdam, E. Hautus

The designer followed the postgraduate programme in technological design, ‘Software Technology’ at the EUT. This resulted in a Ph.D. design project at the Faculty of Mathematics and Computer science of the EUT. The project was executed in the V.U. Hospital Amsterdam at the Department of Clinical Physics and Engineering. The first part of the design project was developed during the post graduate design programme, the next part as a Ph.D. student. The project took three years. The system is in use.

The ‘Sybar’ project was concerned with the development of a motion-analysis system for rehabilitation medicine at the VU hospital in Amsterdam. It was a complex project, combining software design with hardware and mechanics. The functionality of the system was added in a number of steps, using the rapid prototyping method. OMT, one of the methods for object-oriented designing, was used to develop the system. The process structure can be seen as consisting of parallel processes.

The analysed documentation consists of the project report of the postgraduate programme and the Ph.D. thesis.

3.2.2 Case 2 (software engineering)

The design of a new graphical user interface for ExSpect, P. de Crom

The designer followed the postgraduate programme in technological design, ‘Software Technology’ at the EUT. The project was executed in charge of Bakkenist Management Consultants, a Dutch consultancy office. The first part of the design project was developed during this postgraduate design programme, the next part in a co-operation between the faculty of Mathematics and Computer science of the EUT and Bakkenist Management Consultants. The product is delivered and the project is finished.

A new graphical user interface had to be designed for the existing version of ExSpect. ExSpect is an Executable Specification Tool, used for business and system engineering to specify complex distributed systems with discrete time intervals. OMT, one of the methods for object-oriented designing, was used as a design method. The project was very well structured and documented in the early phases. The implementation phase took more time than planned, was not very well structured and almost not documented.

The analysed documentation consists of project planning, user requirements, project assignment, specification document, prototype, final report of the postgraduate programme, implementation (faze A), implementation (faze B), end report, and final release.

3.2.3 Case 3 (mechanical engineering)

Design of a photo-voltaic/thermal hybrid panel, D.W. de Vries

The designer followed the postgraduate programme in technological design, ‘Computational Mechanics’ at the EUT. This resulted in a Ph.D. design project at the Faculty of Mechanical
engineering of the EUT. The project was executed in collaboration with Shell Solar Energy B.V.. The first part of the design project was developed during the post graduate design programme, the next part as a Ph.D. student.

A prototype of a photo-voltaic/thermal hybrid panel that can be placed on the roof of a house is designed and build. The combi panel converts solar energy into both heat and electricity. It is a multi-disciplinary project, in which thermodynamic, optical (physics of PV-systems), mechanical, architectural, production-technical and economical problems had to be solved. No overall design method was chosen. First, concepts were generated using a list of demands, then a model was made for some concepts to estimate the yearly electrical and thermal field. The results were compared and a prototype was build to check the model. After doing experiments, the concepts left behind were evaluated. The resulting concept was optimised.

The analysed documentation consists of the project proposal, the final report of the design course and an article.

### 3.2.4 Case 4 (mechanical engineering)

**Design of an axially controlled spindle unit for high precision diamond turning, M. Renkens**

The designer followed the postgraduate programme in technological design, ‘Mechatronic design’ at the EUT. This resulted in a Ph.D. design project at the Faculty of Mechanical engineering of the EUT. The project was executed in collaboration with Philips Research Laboratories Eindhoven. The first part of the design project was developed during the post graduate design programme, the next part as a Ph.D. student. The project is finished.

By applying a mechatronic approach, a new concept of a spindle unit was developed with improved performance with respect to axial error motions, axial stiffness and functionality, whereas the number of precision components was kept minimal. The total project has been split into two parts. The first part of the project was focused on reduction of the axial error motions and the increase of the axial stiffness of a precision spindle, by applying an active axial spindle bearing. The second part has been focused on the development of an axial motion control of the spindle. The feasibility of the presented concept has been demonstrated on the basis of the prototype that has been built and tested. A patent application of this design and the corresponding method of making non-rotationally symmetric products have been made. A supplementary development is necessary to let the product operate in a production environment. It was a very multi-disciplinary project combining mechanics, electronics and different make-technologies.

The analysed documentation consists of the final report of the design course and the dissertation.

### 3.2.5 Case 5 (architecture)

**The ‘marché Rose’- cultural trade centre in Bamako, J. Bierman**

The design project was executed as a final project at the EUT, Faculty of Architecture, Department Production and realisation. With this project, the designer won the Archiprix 1996. This is a competition for the best plan by a Dutch student of one of the institutions that teach design in the Netherlands. The project is finished but will not be executed.

The project was a combination of research and designing. The designer studied and made a structural sketch for the trade centre of Bamako, capital of Mali. A design for a market place that burned out in the centre, The Marché Rose, was made. The designer tried to incorporate a lot of different aspects and worked on different levels of abstraction. A lot of hard working was done. Almost all the decisions were well underpinned, referring to the information collected during the research. For this reason, the designer was called ‘analytic’ designer.

The analysed documentation consists of the final report of the study architecture and some mock-ups.
3.2.6 Case 6 (architecture)

Strategitectuur, C. Arts

The design project was executed as a final project at the EUT, Faculty of Architecture, Department Production and realisation and Department of Architectural Design. Three designs were made and a research was done. With one of this sub-projects, the designer was nominated for the Archiprix 1997. None of the projects will be executed.

For every sub-project, the designer ‘designed’ constraints. These constraints form the rules of a ‘game’. He played the game following the rules to develop concepts. When the resulting images didn’t please him, he changed the rules until he felt happy about the result. This strategy helped him to take decisions. The different rules he started from are: constraints for the play field of a laser quest, a literally translation of the program of demands for a building for family of very ill children near a hospital, some energy rules for using transparent material, and constraints of form and structure for a student hotel.

The analysed documentation consists of the final report of the study architecture.

3.2.7 One case described in the terminology of the design philosophy

In Table 3.6, main characteristics of the analysed design processes of case 3 are described in the terminology of the developed descriptive results, i.e. in the terminology of the design philosophy.

<table>
<thead>
<tr>
<th>DESIGN OF A HYBRIDE PHOTOVOLTAIC / THERMAL PANEL, DOUWE DE VRIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Important properties of the product being designed:</td>
</tr>
<tr>
<td>Important viewpoints: thermodynamic, optical, mechanical, architectural, production-technical, and economical.</td>
</tr>
<tr>
<td>Important properties of the design process:</td>
</tr>
<tr>
<td>Requirements and a planning formed the basis for a structured way of working.</td>
</tr>
<tr>
<td>Time constraints and quality requirements drove the process.</td>
</tr>
<tr>
<td>Important factors in the design context:</td>
</tr>
<tr>
<td>Stakeholders that were directly involved:</td>
</tr>
<tr>
<td>− a company of solar cells</td>
</tr>
<tr>
<td>− a company of sun collectors</td>
</tr>
<tr>
<td>− the Energy Centre of The Netherlands</td>
</tr>
<tr>
<td>− TNO</td>
</tr>
<tr>
<td>− TU/e: Department of Mechanical Engineering and the program Computational Mechanics (SAI program)</td>
</tr>
<tr>
<td>Other stakeholders: Architects</td>
</tr>
<tr>
<td>The stakeholders were important because:</td>
</tr>
<tr>
<td>− the companies offered possibilities for realising a prototype</td>
</tr>
<tr>
<td>− the Department of Mechanical Engineering influenced the viewpoints mentioned above</td>
</tr>
<tr>
<td>− the SAI program demanded extensive computations to be performed (these were, however, not necessary for the project)</td>
</tr>
<tr>
<td>− a technically good solution was rejected because of a low architectural (esthetical) quality</td>
</tr>
<tr>
<td>Important design activities:</td>
</tr>
<tr>
<td>Main activities: thinking of concepts (qualifying), modelling (quantifying), and documenting decisions. It was an iterative design process: For each concept, a model was made, experiments were performed, and the model was evaluated. Important were also the discussions with other junior designers, the contacts with the companies, and the discussions after presentations of the (preliminary) results.</td>
</tr>
</tbody>
</table>

Table 3.6: Main characteristics of the design process of case 5.
4 Case studies of the expert designers

The goal of this chapter is to offer detailed information about the case studies of the expert designers. Section 4.1 describes the protocol used to perform the case studies. Section 4.2 summarises one case of the expert designers.

4.1 Detailed protocol

The case-study protocol describes the course of one case, like a script or scenario to be followed. Also for the expert designers, one case study includes two interviews (one general and one more specific). These interviews also have to be prepared, performed, processed (transcribed to a transcription scheme), and summarised in a report. Also, a study of the documents offered by the designer must be made. Below, each of the activities of the protocol is documented.

4.1.1 Preparation of the first interview

The preparation for the first interview with expert designers was identical to the preparation of the first interview with the junior designers. The introductory document sent to the designers, however, was different, because the contents of the interviews of the junior and expert designers were different. Together with the introductory document, short summaries of the junior designer cases (see Section 3.2) and preliminary results of a cross-case analysis of the junior cases (see Section 6.1) were sent to the expert designers.

1. personal introduction
   see CV/homepage
2. description of my research project
   Towards a multi-disciplinary framework for design
   Isabelle M.M.J. Reymen, Stan Ackermans Institute, Eindhoven University of Technology
   prof.dr.dipl.ing. D.K. Hammer (computer science, EUT)
   prof.dr.ir. M.F.Th. Bax (architecture, EUT)
   prof.dr.ir. J.E. van Aken (management, EUT)
   prof.dr.ir. P. Kroes (philosophy, TUDelft)

Problem statement:
There is an increasing awareness about the gap between general design theory (if exists) and design practice. Key elements in my investigation are a multi-disciplinary approach and the practice as a starting point.

Objective:
This project has two main goals. The first goal is to inventory, describe, model and compare the most important aspects, generic methods, and problems of design situations in different design disciplines in practice (descriptive). The second goal is to consider in detail one aspect in relation to a bottleneck in the design situation, to develop an application for the design practice (prescriptive).

Research question first goal:
Which are the most important characteristics of design situations in practice?
- Which are similarities of design situations in the different design disciplines?
- Which are the main differences in design situations in and between the three disciplines?
- Which are the most important bottlenecks of the design process in practice?
- Which characteristics of designing are underexposed in the different design disciplines?
Methodology:
In twelve case studies, junior and senior designers in different disciplines at the university and in practice are interviewed. The chosen disciplines are computer science, mechanical engineering and architecture. The first six cases with young designers in the three disciplines are already executed. After a short analysis period, the next six cases with professional designers are started. The cases will be compared for similarities and differences. A multi-disciplinary framework for design will be generated as a tool to describe design situations in the different disciplines. The results of the cross-case analysis and of a literature study will be combined to answer the research question.

3. description of the course of a case-study
First, the professional designers are asked to discuss one of their design projects. Then, more general statements about their design discipline will be discussed.

Part one: design situation
The question list contains questions about the following topics:
- The product
- Designing
- The design process
- Management
- What is learned about designing in this project
- Other aspects of designing on the level of your project.

Part two: design discipline
To check my view of your discipline, made by the first two case studies of junior designers in your discipline and by some literature study, some preliminary results will be presented. Enclosure, you will find
- Short summaries of the junior designer cases
- Preliminary results of a cross-case analysis of the junior cases

We will talk about the topics of part one on the level of your company and your discipline.

This interview will take one hour and a half. Afterwards, a summary report will be made of the interview and of the analysis of the documents. The remarks about the design discipline will be processed.

If possible, you are asked to make a short preparation for this interview:
Look for some documentation of at least 3 (representative) stages in the development of the product in a chosen project (including first and final stage). Possible documents: project description (specifications), product description, process description.

The summary report will be send to you to give your remarks. Possibly, we will discuss some topics more in detail in a second interview. Afterwards, the final document will be made.

Table 4.1: Introductory documentation sent to the designer.

4.1.2 First interview
The goal of the first interview was to get a broad overview of the project, following a general question list. The first interview was planned to take one hour and a half. In Table 4.2, the question list used for the first interview is presented. Fields of attention in the first interview with the expert designers were the product being designed, the design process, management of the design process, and things learned from the project. The expert designers were also asked to give feedback on the summary I made about characteristics of design processes in their design disciplines and to give their opinion on similarities between designing in their disciplines and other disciplines. Again, the structure of the question list is made in English; the questions are formulated in Dutch, because all interviewees were Dutch.

Table 4.2: Question list used for the first interview.

INTRODUCTION
1. questions, remarks about research project, case studies, other
2. agreement on duration of interview (1.5h)
3. appointment for the second interview
4. questioning difficulties with audio-recording
5. overview interview
QUESTIONS
(I made two lists: one about an executed project: talk about history, past tense of questions; one about design projects in general, present tense of same questions)

General facts
- Education, university, title
- Executed design projects (experience)

Part 1: design situation (Project)

Product
Wat werd er ontworpen?

Hoe zou u de omgeving en het systeem beschrijven over de hele levenscyclus van het product? Welke product aspecten zijn belangrijk?
Wat waren de specificaties? (evolutie)

Welke ontwerp dilemma bent u tegengekomen? Hoe werden ze opgelost?
Wat waren hierbij de belangrijkste kennis- en inspiratiebronnen?

Welke materialen (middelen) stonden ter beschikking voor de verschillende levensfasen van het product?

Hoe werd het product gedocumenteerd?

Designing
Hoe definieert u ontwerpen? Wat is uw ontwerp filosofie?

Process
Hoe zou u het proces nu beschrijven?
(structuur, stadia, fasen, toestanden van proces en product)

Werd er gewerkt volgens een voorbeeld?
(theorie, strategie, methode, model, case, conventie, bedrijfscultuur)

Welk waren andere beschikbare hulpmiddelen en welke werden gebruikt tijdens het ontwerpproject? (techniek, tool; medium)

Welk waren de belangrijkste activiteiten tijdens het ontwerpproces?
(alternatieven genereren, kiezen, beslissen, verantwoorden, evalueren, communiceren, documenteren)

Wat ziet u als belangrijke vaardigheden voor het ontwerpen?
(creatieveiteit, intuitie)

Welk waren de verschillende partijen, deelnemers en betrokkenen en welke waren hun standpunten tijdens het project? Waaruit bestond het ontwerp team?

Wat waren verstoringen, traumatische elementen van het proces? Hoe werden ze opgelost?

Welk was de meest belangrijke beslissing in het project? (waarom, hoe opgelost, ...)

Hoe werd het proces gedocumenteerd?

Management
Hoe definieert u project management?
Welke ‘management’ activiteiten werden uitgevoerd tijdens het project?

Learned
Wordt de opgedane kennis van dit project meegenomen in andere projecten? (feedback)

Other aspects of designing
Geef 3 aspecten die belangrijk zijn voor het ontwerpen en die nog niet genoemd zijn.

Part 2: design discipline (preliminary results)

In hoeverre is het product en de gevolgde aanpak (proces) standaard (representatief) voor uw bedrijf en discipline?

Wat zijn voor u de drie meest belangrijke ‘bottlenecks’ in uw domein?
(Welke ontwerpproblemen zouden beter ondersteund kunnen worden?)

Welk probleem zou het eerst aangepakt moeten worden? Hoe?
4.1.3 Processing data of the first interview

During the first interview, notes were made and a tape recorder was used. To process the data of the first interview, first, the interview notes were completed during listening to the tape. Then, the rough interview notes were summarised in Dutch and a code corresponding to the transcription scheme was given. The transcription scheme for the expert cases is presented in Table 4.3. Then, the documents received from the designers were analysed and the relevant information was transcribed to the same scheme. Finally, a summary of the case is made.

Table 4.3: Transcription scheme.

4.1.4 Preparation of the second interview

The preparation of the second interview included the same activities as for the first interview, except that a specific question list must be made for the second interview for the specific case. The designer was asked to write down ideas and comments which came to him/her after the first interview and which could be interesting for me.
4.1.5 Second interview

Topics for the second interview concerned questions that remained unanswered after the first interview, questions about the documentation, and specific questions concerning the specific project. Also, the summary of the first interview was checked and ideas and comments of the interviewee in relation to the first interview were discussed. The course of the second interview is given in Table 4.4.

<table>
<thead>
<tr>
<th>Introduction</th>
</tr>
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<tbody>
<tr>
<td>1. explanation of the goal of the second interview</td>
</tr>
<tr>
<td>2. description of the interview scheme (see conversation)</td>
</tr>
<tr>
<td>3. agreement of duration of interview (1.5h)</td>
</tr>
<tr>
<td>4. description of the processing of the information of the interview</td>
</tr>
<tr>
<td>5. asking for questions, obscurities</td>
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<table>
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<tr>
<th>Conversation</th>
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<tbody>
<tr>
<td>The interview scheme of the conversation depends on the specific case. The general content of the conversation is as follows:</td>
</tr>
<tr>
<td>− control summary of interview one</td>
</tr>
<tr>
<td>− discuss ideas and comments of interviewee</td>
</tr>
<tr>
<td>− ask the questions of the specific question list.</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. summary of the conversation</td>
</tr>
<tr>
<td>2. thanking for co-operation</td>
</tr>
</tbody>
</table>

Table 4.4: Scheme for the second interview.

4.1.6 Processing data of the second interview

To process the data of the second interview, the same activities as for processing the data of the first interview were performed. The summary of the case and of the documentation have been corrected according to the comments of the designer and new insights.

4.1.7 Summary report case

The procedure to make a summary report of each of the cases was the following:
− make a short summary of the contents of the case;
− include a summary of the interview in Dutch;
− make a summary of the documentation;
− make a document of the transcribed contents of the case;
− add question list 1;
− add question list 2;
− add introduction to the designer.

4.2 Summary of one case

In Table 4.5, the main characteristics of the analysed design process of one expert designer (case 13) are described in the terminology of the design philosophy, one of the developed descriptive results in the Ph.D. project. This description uses the chosen domain-independent terminology to describe design processes. It is claimed that all cases could be described using this terminology, which evolved out of the transcription scheme. The case is an example of the design of utility buildings in architecture.
DESIGN OF A WASTE-TRANSHIPMENT STATION, XX ARCHITECTS

| Important properties of the product being designed: | The problem of waste transhipment, the logistics, the location (near water and housing), the planning of the execution in phases, the town planning, the soil, the building (protection against noise and smell, quality of the façade, large span, human scale), the re-use of materials, the energy usage, the durability, the climate |
| Important properties of the design process: | The use of phases as milestones; the interaction with different stakeholders at the beginning of the design process |
| Important factors in the design context: | Important stakeholders: |
| | – Architects office |
| | – Project-management office |
| | – Commissioner |
| | – Government (determines rules, gives permissions) |
| | – Contractor (must build the design) |
| Important design activities: | Drawing, estimating building cost, making details, making models, discussing, determining strategy |

Table 4.5: Main characteristics of the design process of one expert case.
5 Approach to the cross-case analysis

The case studies, summarised in a single report per case, offered empirical material for a cross-case analysis. The cases were compared for similarities and differences within one discipline and in different disciplines. A preliminary cross-case analysis was based on the cases of the junior designers; preliminary conclusions concerning similarities and differences between the three chosen disciplines can be found in Section 6.1. After the cases of the expert designers were performed, a cross-case analysis was based on both the junior and expert cases. A description of design processes in each discipline was made based on the mutual comparison of the cases per discipline; the description of these processes can be found in Section 6.2. These descriptions were compared to make a general description of design processes, including domain-independent characteristics of design processes transceding disciplines. In this general description, synonyms for the different terminology used in the three disciplines were introduced. (Some terms are shared between disciplines, but these terms often have a different content or meaning in the different disciplines.) The general description of design processes evolved to a design philosophy and a design frame, the final descriptive results of the Ph.D. project; the design philosophy and design frame are described in Chapters 3 and 4 in [Reymen, 2001a]. At the end of the research project, general conclusions concerning the cross-case analysis were drawn, based on a reflection on the cross-case analysis; these conclusions can be found in Section 6.3.

6 Results of the cross-case analysis

The goal of this chapter is to give insight into the evolution of the results of the cross-case analysis. Section 6.1 describes the results of a preliminary cross-case analysis based on the junior cases. Section 6.2 describes the results of the cross-case analysis performed when the junior and expert cases were finished. Section 6.3 gives conclusions made at the end of the research project. The results have no scientific value other than that they illustrate the evolution of the concepts in my project, which is a process point of view.

6.1 Preliminary results

First, conclusions based on similarities and differences are described. Then, in Table 6.1, an overview of the most important characteristics of design situations in software engineering, architecture and mechanical engineering is given. In the left-hand column of the table, the topics of the transcription scheme used to transcribe the cases of the junior designers are represented.

**Similarities**
(1) Designers are often not aware of their design process and focus mainly on the product. Describing their design process is seen as difficult.
(2) Designing is an iterative process.
(3) There is a big resemblance between the skills all the designers mentioned as necessary for designing.
(4) The underpinning of design decisions is underexposed in the three disciplines, in practice and in education.

**Differences**
(1) Non-technical aspects are underexposed in the literature of software and mechanical engineering.
(2) In the practice of architecture, no explicit use of methods is made.
Architects learn designing already during their education by executing design projects.

<table>
<thead>
<tr>
<th></th>
<th>SOFTWARE ENGINEERING</th>
<th>ARCHITECTURE</th>
<th>MECHANICAL ENGINEERING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Environment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System</td>
<td>Immaterial product</td>
<td>Material product that creates immaterial space</td>
<td>Single or mass-product</td>
</tr>
<tr>
<td>Specifications Design</td>
<td></td>
<td></td>
<td>Design for ‘X’</td>
</tr>
<tr>
<td>Design</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Definition</td>
<td>General definition of designing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Underexposed Aspects</td>
<td>Underpinning of design decisions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Education</td>
<td></td>
<td>Design projects during education</td>
<td></td>
</tr>
<tr>
<td>Process Activities</td>
<td></td>
<td>Not aware of design process</td>
<td></td>
</tr>
<tr>
<td>Resources</td>
<td>Tool set: many methods, different ‘languages’</td>
<td></td>
<td></td>
</tr>
<tr>
<td>People</td>
<td>Similar necessary design skills</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Managing</td>
<td></td>
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</table>

Table 6.1: Overview preliminary conclusions about similarities and differences in design situations of software engineering, architecture and mechanical engineering.

6.2 A description of design processes in each discipline

A description of design processes in the disciplines software engineering, architecture, and mechanical engineering is made, based on similarities between the cases of each discipline. The description is given from the viewpoint of design situations. The structure of the text is based on the topics of a version of the transcription scheme used to transcribe the cases.

6.2.1 Design situations in software engineering

A design situation is characterised on every moment by the state of the product and of the design process. Software engineering can be described as being concerned with transformations in the life cycle of the product, software.

Important for every product are the environment, the system itself and the relations between both. In software engineering, the environment of the system are the users of the software. These can be people as well as machines. The system interacts with its environment through the interface. The software can be embedded software as well as application software. Software is an immaterial product, basically only working with signals.

The most important dimensions of the product can be summarised in two categories. The first category, the basic dimensions, groups the static structure, the dynamic behaviour and the relations between both. The architecture, the objects and the data can describe the static structure. Processes, functions and data-flow, can describe the dynamic behaviour. The second category contains the dimensions linked to the life cycle of the software system. The phases in the life cycle of the product are design, implementation, use and re-use. Dimensions in these different phases can be makeability, timelyness, dependability (reliability, availability, safety, security, robustness), efficiency, quality, correctness, compatibility, modular, flexibility, extendibility, maintainability, reusability, openness and interoperability. All these dimensions can be seen on different levels of abstraction.

The specifications define the constraints on the different dimensions. A software project is complex when the specifications contain many constraints on different dimensions. To get the desired external behaviour of the system clear, the designers can communicate with future users of the system. The following ‘specification’ documents can be made: domain analysis, problem statement, requirements definition, requirements specification and models of the relation of the system with the environment. Also prototypes can be made to...
facilitate the discussions with the user and to check the specifications. The specifications change during the
design-process: some are sharpened, some are added, and some are deleted.

The design gives the way by which the desired behaviour can be achieved. To take into account all the
dimensions, an amount of knowledge exists and is or is not available to the designer. Designers can
communicate to obtain the knowledge they do not possess. Alongside the knowledge and technology of software
development, knowledge about other disciplines like mechanics (e.g. kinematics) and electronics (hardware)
can be necessary to develop an application. The problem is usually decomposed in sub-problems. In design
documents, different dimensions of the product are worked out and described in models and text. The
implementation finally results in code. Designers normally document the product architecture (system design)
and the components (objects) belonging to the system.

Designing can be seen as the thought process comprising the creation of an entity. This seems to be an iterative
process of first intensive and concentrated working on a problem, then leaving the problem for a while, for
finally finding possible solutions when the designer is not busy with the problem. Designing is learned by doing,
in practice.

The most dominating design philosophy in computer science is that of systems theory. This is also reflected in
the terminology used. A lot of knowledge is based on mathematics and logic, exact knowledge. Quantitative
seems to be elevated above qualitative.

The design process consists of the following important activities: defining the specifications, designing the
system, implementing the text into code, and verifying the solutions. There exists no sharp boundary between
design and implementation.

During every activity, the designer takes design decisions and solves the occurring design dilemmas. The
designers are not conscious of what they are doing, during they are doing it. This also holds for design decisions.
‘You know that you made a design decision, after you have seen the impact.’

Implementation takes normally more time than planned, is in most cases not very structured and is very bad
documented. Documenting the design is seen as a very instructive, time absorbing, not pleasant, but necessary
task. Almost every designer admits that he/she documents too less.

The designers must choose a tool-set for specification (analysis), design, programming, and verification and
validation. A tool-set can comprise a design method, a development platform, compilers, CASE tools and/or
specific libraries. A language corresponds with every tool. Software engineers talk about a ‘specification
language’, a ‘design language’ and a ‘programming language’. Usually, the chosen methods and tools structure
the activities in the design process. For software engineering, a big amount of methods exists. The design
methods cover only a part of the design process. The methods are usually not strictly followed. All the software
designers have knowledge of at least one design method and programming language. One of the most used
design methods is object-oriented programming. OMT, object modelling technique, is a well know and much
used technique. This technique is now succeeded by UML, unified modelling language. In OMT, the
specifications are written down during the ‘analysis’ phase. The design-phase is divided in top-level design,
system design and object design. An important technique to make fast prototypes is the ‘Rapid Prototyping’
method. Besides a computer, software engineers also use pencil and paper as a design medium.

The most important skills for designers are: knowing to analyse problems, being creative, daring to reject
solution paths, and having good communication skills. Skills linked to the first one are identification with the
users, seeing the difference between primary and secondary things, working structured, and keeping an overview
of the product and process. To be creative, you must be interested in and have some knowledge of a broad field
of aspects. This also implies that you must see where interesting things can be found. You must be enable to
change the direction for finding a solution. For that reason, you may not stop too early and stay critical, because
perfection is important. Communication skills are necessary to reproduce ideas for you and for other people, like
other designers as well as the commissioners (who speak another ‘language’). You need the means to
communicate with them, for example by language, drawings or sketches, or by simulations. The communication
with other designers is usually very informal. Good communication also means listening to other people and
being open for solutions of other people. Without good communication skills, it will not be possible to convince
other people of your ideas, which can be necessary to ‘sell’ your design. Software engineers must being capable
to think abstract, because of the ‘immateri al’ product they are designing.

In software design teams, a distinction is made between designers and programmers.

The most important dimension of the design process is the time. Important constraints of the design process are
‘easy to design’, and ‘not too much design and implementation work’. Except of a single planning, almost no
documentation of the software design process is made.
Designing a product and managing a process are seen two different activities.

The biggest bottlenecks I see in the design process of software engineers are the planning problem and the need of documenting the important design decisions of the product.

In the literature, underexposed aspects with respect to designing are creativity, the design context, and the importance of culture of designers and social aspects of designing. A good work in which these aspects get attention is [Winograd, 1996].

In the literature of software engineering, many references to Architecture are given.

### 6.2.2 Design situations in architecture

A design situation is characterised on every moment by the state of the product and of the design process. Architecture can be described as being concerned with transformations in the life cycle of the product, buildings in general.

Important for every product are the environment, the system itself and the relations between both. In architecture, the system can be a building of one of the following types: houses, apartments, offices, public buildings (schools, …), and industry complexes. The environment of the system can be the inner environment of the building with its users, and the outer environment being the space around: the neighbours, village, city, infrastructure, … The product has a direct influence on the public space and is therefore part of the public debate. Architecture is a material product, which creates immaterial space.

The most important dimensions of the product (the building as well as the environment) can be summarised in two categories. The first category groups the basic dimensions. These are the static structure, the dynamic behaviour and the relations between both. The construction and the components as a part of the whole form can describe the static structure. Social economical, cultural, physical and building technical dimensions are important. Architectural elements can be light, space, form, colour, material, composition, proportion, and climate. The functions of the spaces and the behaviour of the installations can describe the dynamic behaviour. The second category contains the dimensions linked to the life cycle of the product. The phases in the life cycle of a building and his environment can be: (history), development, production, transport, realisation, use, extension, rebuilding, renovation, demolition, and recycle. Important dimensions linked to these phases can be: prefabrication, building time, realiseability, usability, build for permanence, milieu, energy, flexibility, modularity, safety, maintainability (cleaning), and reuse of material. All these dimensions can be seen on different levels of abstraction.

The specifications define the constraints on different dimensions. Standard specifications for architects are the program of demands (functional specification, budget, surfaces, when ready to use), the situation (location) and the legislative restrictions local and national or international. The specifications can be qualitative as well as quantitative. The economic constraint is usually very strong. An architectural project is complex when the specifications contain many constraints on different dimensions. The complexity of a building can then be a combination of the size of the system, the difficulty of the program of demands (different engineering techniques), the location (historical, soil, environment) and the legislative restrictions. To get the specification clear, architects can communicate a lot with the future users, they can make analysis’ of the location and can study the constraints given by the law. The last ones are fixed, the others can be made and changed by mutual agreement of the partners. For the communication, architects make models, schemes, prototypes (mock-ups) and presentation drawings. In some cases, room content descriptions specify the demands of every room. The relation of the product with the environment is usually seen as very important. The specifications change during the design-process: some are sharpened, some are added and some are deleted.

Architects usually want to design a product that satisfies the specifications and the demands they make for themselves. These can be giving importance to one dimension (e.g. the indoor climate or a curved form), or making ‘Architecture’ to say something in the debate of architecture or to make a piece of art.

To take into account one or more important dimensions of the future product, a lot of knowledge and experience exist. Important knowledge for designing architecture may be knowledge about ergonomics, activity patterns, proportions, and types. This knowledge becomes implicit after some years of designing. There is a lot of knowledge necessary to make an executable design, but architects can already design with some rules of thumb. Qualitative aspects dominate the design process in the first stages of the process. To incorporate the more technical dimensions, architects usually work together with specialists of different sub-disciplines like logistics, soil, foundations, construction (stability), building physics, installations (electricity, lighting, heating, sanitary), garden, and decoration. There is always a tension between the ideas and feelings of the architect (also aesthetic
Architects are not afraid of very hard working. The most important skills for designers are: knowing to analyse disciplines, executors and intermediates (project management offices). In the design team, a difference is made between means for studying the development of the product and means for presentation to the commissioner and/or the users. Architects don’t speak much about design methods. They just organise and plan the execution process. After the realisation, ‘as built’ documents can be made which represent the realised building. Architects usually have a systematic way of coding their documents (version, date). Also, they write down the most important decisions of every meeting. This is necessary because of the responsibilities of the different participants, and the corresponding cost consequences.

Designing can be seen as the thought process comprising the creation of an entity. This seems to be an iterative process of first intensive and concentrated working on a problem, then leaving the problem for a while, for finally finding possible solutions when the designer is not busy with the problem. Architects learn designing already during their education by executing a lot of projects of increasing complexity.

The design philosophy of architects can be situated between two extremes. The first extreme is the intuitive architect. For him, the following words are taboo: testing, rationality, analytical, hierarchy, systematic. The other extreme is the analytical, rational designer who tries to underpin every decision. For all architects, social aspects, feelings and the society as a whole are important. The design philosophy of an architect is very personal and is reflected in his products. Architects have a special link with the products they make (designed by ‘X’, not anonymous). Architects don’t want to use ideas of other architects.

The most important structure of the design process of architects is the increasing level of detail. The different levels get the following names: analysis of location and of program of demands (high level), formulating demands (lower level), sketch design, preliminary design, definitive design (or realisation design, materialisation), and ‘as build’. On the first level, the functional relationships, the relation of the product with the environment, the wished identity of the complex and parts, and the possibilities of use can be analysed and the feasibility of the project can be studied. The structure of the process is interwoven with economic aspects, namely the payment in phases. The design process stops when the planned design period is come to an end, or when the specifications are fulfilled and the architect is satisfied with the design. The names of the different levels mentioned above correspond also with the most important activities and the names of the drawings made. These periods of working on a certain level of detail are also called ‘phases’. The design process has a very strong milestone, namely the receiving of the building permission (municipal approval).

During every activity, the designer takes design decisions and tries to incorporate as much important dimensions as possible. To make a concept (as a starting point), one idea is put in the centre. Then, holding the concept, the occurring design dilemmas are solved. Talking to other people helps to find solutions.

A lot of good designs will not be realised because they are made for a competition (and didn’t win), or because of other reasons.

The architect stays responsible for ten years for mistakes in some parts of the buildings.

The resources that can be used by architects are CAD (computer aided design), drawings and sketches on paper, mock-ups, calculation tools, methods for time and cost estimation, planning tools, and simulation tools. The design media can be pencil and paper, mock-ups and three-dimensional drawings (possibly made by computer). A difference is made between means for studying the development of the product and means for presentation to the commissioner and/or the users. Architects don’t speak much about design methods. They just organise themselves so that they can work the best.

The important people in the design process of a building can be the architect, commissioner, designers in other disciplines, executors and intermediates (project management offices). In the design team, a difference is made between designers and drawers. Talking to other people helps to stay critical.

Architects are not afraid of very hard working. The most important skills for designers are: knowing to analyse problems, being creative, daring to reject solution paths and having good communication skills. Skills linked to
the first one are identification with the users, seeing the difference between primary and secondary things, working structured and keeping an overview of the product and process. To be creative, you must be interested in and have some knowledge of a broad field of aspects. This also implies that you must see where interesting things can be found. You must be able to change the direction for finding a solution. For that reason, you may not stop too early and stay critical, because perfection is important. Communication skills are necessary to reproduce ideas for you and for other people, these are other designers (you work with) as well as the commissioners (who speak another ‘language’). You need the means to communicate with them, for example, by language, drawings or sketches (possibly three-dimensional), mock-ups or simulations. Good communication also means listening to other people and being open for solutions of other people. Without good communication skills, it will not be possible to convince other people of your ideas, which can be necessary to ‘sell’ your design. Architects must also be able to think in three dimensions. Architects are usually ‘possessed’ by their project until it is finished.

The most important constraints of the design process are the time, the money and the satisfaction of the designer. During the design process, a planning of the process is made. The reason for going beyond the time limit, is usually the fact that unknown important knowledge appears or that the designers can’t decide to stop and are not satisfied with the result.

Managing is seen as an activity different from designing. Usually, people who are not part of the design team (internal or external) execute the management activities. The management people have a more businesslike approach, more rational (not the designer ‘X’ with his design philosophy). They can co-ordinate the different engineers, control the budget and make contracts.

The biggest bottleneck I see in the design process of architects are the planning problem and the acceptance of the rational element in designing.

In the literature and culture of architects, underexposed aspects with respect to designing are the rational approach of underpinning design decisions.

6.2.3 Design situations in mechanical engineering

A design situation is characterised on every moment by the state of the product and of the design process. Mechanical engineering is concerned with transformations in the life cycle of the product.

Important for every product are the environment, the system itself and the relations between both. In mechanical engineering, the system can be a consumer product or a production-system. This can be a single product or a product for mass-production. The environment of the system can be the consumer or operator and hardware or production-systems.

The most important dimensions of the product can be summarised in two categories. The first category groups the basic dimensions, being the static structure, the dynamic behaviour and the relations between both. The construction and the form of the system can describe the static structure. The functionality and the processes can describe the dynamic behaviour. The second category contains the dimensions linked to the life cycle of the product. The phases in the life cycle of the product are (history,) development, production, marketing, re-engineering and recycling. Important dimensions linked to these phases are described in literature as ‘Design for X’, and can be manufacturing, maintenance, modularity, safety, makeability, robustness, reusability. The most important one is the makeability. All these dimensions can be seen on different levels of abstraction.

For the specifications of the product, mechanical engineers usually refer to existing products or components. They want to optimise these products by combining different components or by using different techniques. The designers define their own constraints and change the specifications during the design process: some are sharpened, some are added, and some are deleted. A project is complex when the specifications contain many constraints on different dimensions.

Mechanical engineers can design for different phases in the life cycle of the product. They can design in a research and development environment, they can design a product or a production process, they can optimise the production-process, or they can design the re-use of a product.

To take into account all the different dimensions, an amount of knowledge exists and is or is not available to the designer. Designers can communicate with experienced designers, specialists, machine-builders and users to obtain the knowledge they don’t possess. To design in mechanical engineering projects, a lot of knowledge from different design fields is necessary, for example knowledge of thermodynamics, optics, construction, electronics, production techniques. Also economic aspects play a role. Mechanical engineers can choose out of a wide range of materials, each with their own characteristics.
In design documents, different dimensions of the product are worked out. These are normally the product architecture and the components belonging to the system. Designers make models of the system with the environment, they document alternatives (different concepts), they design prototypes and they make drawings of the product in two and three dimensions. Starting with a lot of possibilities, they end with one solution. Product data systems can store the information (documentation) of the product.

**Designing** can be seen as the thought process comprising the creation of an entity. This seems to be an iterative process of first intensive and concentrated working on a problem, then leaving the problem for a while, for finally finding possible solutions when the designer is not busy with the problem. This iterative cycle can also be specified as generating concepts (qualitative), modelling (quantitative) to underpin the choices and documenting the decisions for communication. Designing in mechanical engineering is learned by doing and almost not during the education.

Two extreme design philosophies seem to exist in mechanical engineering. The first one is methodical, systematic working following a design method, the second is designing free, without a prescriptive method, to find a solution that meet the requirements. This last philosophy is more pragmatic and recognised by me in practice.

The **design process** consists of the following important activities: generating concepts, modelling, make estimations, calculate, building a prototype or make simulations to check the model by doing experiments, evaluating the results and optimising the resulting concept. During every activity, the designer takes design decisions and solves the occurring design dilemmas. The designers are not conscious of what they are doing, during they are doing it. Documenting the design is seen as a very instructive, time absorbing, not pleasant but necessary task. Almost every designer admits that he/she documents too less. The specifications and the level of detail can obtain the structure of the design process. Mechanical engineers use pen and paper, CAD/CAM tools, and calculation tools during the design process.

The most important skills for designers are: knowing to analyse problems, being creative, daring to reject solution paths and having good communication skills. Skills linked to the first one are identification with the users, seeing the difference between primary and secondary things, working structured and keeping an overview of the product and process. To be creative, you must be interested in and have some knowledge of a broad field of aspects. This also implies that you must see where interesting things can be found. You must be able to change the direction for finding a solution. For that reason, you may not stop too early and stay critical, because perfection is important. Communication skills are necessary to reproduce ideas for you and for other people, these are other designers as well as the commissioners (who speak another ‘language’). You need the means to communicate with them, for example by language, drawings or sketches (possibly three-dimensional), mock-ups or simulations. Good communication also means listening to other people and being open for solutions of other people. Without good communication skills, it will not be possible to convince other people of your ideas, which can be necessary to ‘sell’ your design.

The most important constraint of the design process is the time.

Except of a single planning, almost no documentation of the design process is made.

**Managing** and designing are seen as two different activities.

I did not find big bottlenecks in the design process of mechanical engineers.

In the literature, underexposed aspects with respect to designing are creativity, the design context, and the culture of designers and social aspects of designing. These non-technical aspects are seen as very important during designing in teams.

### 6.3 General conclusions

General conclusions that resulted from the cross-case analysis and that influenced my results very much are the following three. First of all, I noticed that the combination of the product being designed, the design process, and the design context was important in all cases. Second, I learned that designers change both properties of the product being designed and of the design process. Third, I observed that design phases are the major structuring principle of design processes in practice; design phases take long periods in time (usually several months). Design methods guiding designers during a design process are all based on these phases. These phases are also often part of norms and standards (ISO norms, building norms, software standards, etc.); the standards also often justify their use. Shorter periods in time are not used for structuring a design process, although there appeared to be a need for
such a short-term structuring mechanism. This last observation inspired me to introduce the idea of
design sessions (see Section 5.5 in [Reymen, 2001a]).
7 Conclusions

This report offers information about the performed empirical study at the beginning of my research project and about its results; it includes additional information that has not been written down in the Ph.D. thesis [Reymen, 2001a]. Chapters 2, 3, and 4 give attention to the case studies; Chapters 5 and 6 discuss the cross-case analysis. Some final conclusions about the approach to and the results to the empirical study are the following.

The goal of the case studies I performed, namely exploring the design practice and inventorying the most important characteristics of design processes in several disciplines, has been met: I found many differences between design processes in the different disciplines, but I also found common characteristics of design processes, mainly on a general level.

While executing the protocol I developed for the cases studies, I learned that one of the two sources for case-study information I have chosen, namely interviewing designers, has some disadvantages: An interview is too short for discussing a (complete) design project and most of the designers find it difficult to talk about designing. In spite of these disadvantages, I believe that interviews are a useful technique for design research, if they are combined with other techniques. I combined interviewing designers with analysing the documentation of their design projects.
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