Managing Design Rationale in the Development of Product Families and Related Design Automation Systems

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Managing Design Rationale in the Development of Product Families and Related Design Automation Systems

Doctoral Thesis in Machine Design

Managing design rationale in the development of product families and related design automation systems

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ABSTRACT

As the markets’ needs change rapidly, developing a variety of products that meet customers’ diverse needs is a competitive factor for many manufacturing companies. Development of highly customized products requires following an engineer-to-order business process to allow the products to be modified or adapted to new customers’ specifications, which brings more value to the customer and profit to the company.

The design of a new product variant involves a large amount of repetitive and time-consuming tasks but also information handling activities that are sometimes beyond human capabilities. Such work that does not rely so much on creativity can be carried out more efficiently by applying design automation systems. Design automation stands out as an effective means of cutting costs and lead time for a range of well-defined design activities and is mainly considered as a computer-based tool that processes and manipulates the design information.

Variant design usually concern generating a new variant of a basic design, that has been developed and proved previously, according to new customer’s demands. To efficiently generate a new variant, a deep understanding of the intention and fundamentals of the design is essential and can be achieved through access to design rationale—the explanation of the reasons and justifications behind the design.

The maintenance of product families and their corresponding design automation systems is essential to retaining their usefulness over time and adapting them to new circumstances. Examples of new circumstances can include the introduction of new variants of existing products, changes in design rules to meet new standards or legislations, or changes in technology. To maintain a design automation system, updating the design knowledge (e.g. design rules) is required. The use of design rationale will normally become a necessity for allowing a better understanding of the knowledge. Consequently, there is a need for principles and methods that enable the capture and structure of the design rationale and sharing them with the users.

This study presents methods and tools for modeling design knowledge and managing design rationale in order to support the utilization and maintenance of design automation systems. Managing design rationale concerns enabling the capturing, structuring, and sharing of design rationale. The results have been evaluated through design automation systems in two case companies.

Keywords: Design rationale, design automation system, computer-supported engineering design and product development.
SAMMANFATTNING

Att kunna erbjuda kundanpassade produkter har blivit allt viktigare för många tillverkande företag. Utformningen av en ny produktvariant involverar en stor mängd repetitiva och tidskrävande uppgifter men även informationshanteringsaktiviteter som ibland är bortom mänskliga möjligheter. Sådant arbete som inte förlitar sig så mycket på kreativitet kan genomföras mer effektivt genom att använda designautomatiseringssystem. Designautomatisering framstår som ett effektivt sätt att minska kostnader och ledtider för en rad väldefinierade designaktiviteter och betraktas huvudsakligen som ett datorbaserat verktyg som analyserar och syntetiserar designinformationen.

Variantdesign handlar vanligtvis om att skapa en ny variant av en grundläggande design, som har utvecklats och bevisats tidigare enligt nya kunders krav. För att effektivt skapa en ny variant är en djup förståelse för designens avsikt och grundläggande uppbyggnad avgörande och kan uppnås genom tillgång till ”design rationale”- förklaringen av skälen och motiveringarna bakom designen.

Underhållet av produktfamiljer och deras motsvarande designautomatiseringssystem är viktigt för att behålla användbarheten över tid och anpassa dem till nya omständigheter. Exempel på nya omständigheter kan innefatta införande av nya varianter av befintliga produkter, ändringar av designregler för att uppfylla nya standarder, lagstiftningar eller tekniska ändringar. För att upprätthålla ett designautomatiseringssystem krävs uppdatering av designkunskapen (t ex designregler). Användningen av design rationale kommer normalt att bli en nödvändighet för att ge en bättre förståelse av kunskapen. Följaktligen finns det ett behov av principer och metoder som möjliggör fångande och strukturering av design rationale och dela dem med användarna.

Denna studie presenterar metoder och verktyg för modellering av designkunskap och hantering av design rationale för att stödja utnyttjande och underhåll av designautomatiseringssystem. Vid hantering av design rationale gäller det att göra det möjligt att fånga, strukturera och dela med sig av design rationale. Resultaten har utvärderats genom att undersöka effekterna av dem i designautomationssystem i två företag.
ACKNOWLEDGEMENTS

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Managing Design Rationale in the Development of Product Families and Related Design Automation Systems
ABBREVIATIONS

CAD — Computer Aided Design
CAM — Computer Aided Manufacturing
CMM — Computer Measuring Machine
DR — Design Rationale
FEA — Finite Element Analysis
FMEA — Failure Modes and Effects Analysis
PLM — Product Lifecycle Management
Managing Design Rationale in the Development of Product Families and Related Design Automation Systems
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SUPPLEMENTS

The following supplements constitute the basis of this thesis.

**Paper 1**

Elgh was the main author and initiated the study. The discussed framework was developed by Elgh. The work of studying the available methods and applications as well as implementing and evaluating the framework and prototype system was carried out by Poorkiany.

**Paper 2**

Poorkiany and Johansson contributed to developing the model as well as developing and implementing the prototype system. The paper was mostly written by Poorkiany and Johansson contributed to writing the case study. Elgh contributed as a reviewer with advice concerning the work.

**Paper 3**

Johansson contributed to the system architecture and programming effort. The development of the framework, implementation of the prototype system, and tests and demonstrations of the concepts were carried out by Poorkiany and Johansson. The paper was mostly written by Poorkiany and Johansson contributed with the information model. Elgh contributed as a reviewer with advice concerning the work.

**Paper 4**
Poorkiany and Johansson contributed to the development of the framework and implementation of the prototype system. Poorkiany wrote the paper with the support of Johansson. Elgh contributed as a reviewer with advice concerning the work.

**Paper 5**


Poorkiany contributed to interviewing the engineers, analyzing the interviews, and examining the IBIS method in the case company. Johansson and Elgh contributed to holding the meetings and workshops in the company and to analyzing the results of the interviews, and providing suggestions and guides in identifying the research goal and formulating the research project. The paper was written by Poorkiany.

**Paper 6**


Poorkiany contributed to capturing the design rationale from the designers and implementing the IBIS method and templates. Elgh contributed with advice about the overall process of capturing and sharing the design rationale and the product family model. Johansson contributed with advice concerning the work. The paper was written by Poorkiany.

**Paper 7**

M. Poorkiany, J. Johansson, F. Elgh, “Capture, structure and share design rationale in a design family development process”. The paper is submitted to an international journal.

Poorkiany contributed to the “capturing design rationale” part and the QOC method. Johansson contributed the “sharing design rationale” and domain specific language parts. The information model was developed by Poorkiany and Johansson. Elgh contributed as a reviewer with advice concerning the work. The paper was written by Poorkiany and Johansson.
**Additional Supplements:**

**Paper 8**  

**Paper 9**  

**Paper 10**  

**Paper 11**  

**Paper 12**  
CHAPTER 1

INTRODUCTION

CHAPTER INTRODUCTION

Many companies that design and manufacture customized products use design automation systems to reduce cost and lead time and increase efficiency in the development of new design variants. The objective of the presented research work is on supporting utilization and maintenance of the products and their design automation systems to respond to changes over time (e.g., changes in product specification). Managing design rationale is recognized as an important parameter to support system utilization and maintenance.

This chapter first describes the background of the research. Then, the problem area is identified, and the scope and purpose and research questions are discussed. Then, the industrial and scientific contributions, as well as the research projects and case of applications, are described.

1.1 PRODUCT FAMILY DEVELOPMENT

The ability to design and manufacture highly customized products that are well matched to the needs and expectations of customers is a competitive factor for many manufacturing companies. The development of highly customized products requires following an engineer-to-order business process to allow the products to be adapted to new customers’ specifications, which brings more value to the customer and profit to the company.

To stay competitive, some companies aim to develop product families instead of focusing on developing single products at a time. A product family is a set of products that share common components and functions and address a related set of market applications [1]. While a product family targets a specific market segment, each product variant is specified according to individual customer needs [2].

The interpretation of product families depends on different views; for example, the marketing view of a product family is characterized by various sets of functional features for different customers, while the engineering perspective of a product family is characterized by design parameters, components and assembly structures [2].

A key principle in the development of product families is to putting minimum design requirements in the early stages of development. The design decisions are delayed in order to achieve more knowledge and optimal trade-offs. This allows the
establishment of a space of design variants instead of a single variant. The design space maps the design variants to the customers’ specifications.

1.2 DESIGN ACTIVITIES

Sriram et al. [3] classify design activities into four categories: 1) Creative design when there is no prior plan for the solution of the problem or the plan is an abstract decomposition of the problem into a set of levels; 2) innovative design when the decomposition of the problem is known, but there are no alternatives for its subparts so they must be developed (the alternatives might be a novel combination of existing components); 3) redesign when an existing design is modified to meet the required changes; and 4) routine design when a prior plan of the solution exists that involves finding the known and appropriate alternatives.

Studies show that up to 80% of design time is concerned with modifying, adapting or redesigning already existing and proven solutions [4]. Adaptation and variant design usually concern generating a new variant of a basic design, that has been developed and proved previously, according to new customer's demands. This process involves a large amount of repetitive and time-consuming work. Engineers might spend days producing quotation drawings for a customer request, which is time consuming and error prone. To quickly go from answering the quotation, adapting the product to new specifications and moving into production, the utilization of systems and tools for efficient design is required. Those tasks that do not rely so much on creativity can be carried out automatically by implementing the product information and knowledge “in solutions, tools or systems that are pre-planned for reuse and support the progress of design process” [5].

1.3 DESIGN AUTOMATION

The automation of design tasks is an approach many industrial companies take to shorten lead time, improve product performance reduce cost, and adapt products to customer specifications [6]. “Design automation is a computer-based methodology to partly or wholly automate tasks in engineering design by applying modern software technology to do the work of the human designer” [7].

Design automation systems often facilitate the documentation and maintenance of knowledge and enable the designers to focus their work on solving problems that need skill, experience, and creativity [8]. Selecting and defining the task(s) to be automated is the main step when planning a design automation project. Repetitive, time-consuming and information handling tasks that are sometimes beyond human capabilities and that do not involve creative problem solving are well suited for automation [9]. It is hardly conceivable to automate the design process in its entirety. Therefore, typical design automation applications are mostly aimed at optimizing only those parts of the process where the cost/benefits are particularly favorable [10].
1.4 PROBLEM AREA

Product development is a deliberative process that involves a multitude of decisions that transform the market needs into a product [11]. Product development decision making is iterative and characterized by uncertainty and long feedback loops that require a large amount of resources [12]. In the early stages of the development process, the engineers know less about the design problem. But as the development process continues, the engineers’ knowledge about the problem and alternative solutions increases.

A company’s unique intellectual capital is built, to a large extent, on the gained experiences and knowledge from its own product development process [13]. The engineers put a lot of effort toward making the right decisions; however, the results of evaluating the design alternatives and tradeoffs and the argumentations that lead to a decision are usually not documented and exist only in the engineers’ minds [14]. As the development proceeds, or even after releasing a product to the market, some decisions that have been made during the early phases might need to be reviewed, edited, or rejected as soon as more detailed knowledge, new customer demands or new technology in the company is available. Therefore, it is important for the engineers to understand the reasons and arguments behind the design decisions. Accordingly, it is important for the companies to support their engineers by providing methods and systems to capture and share the decisions as well as the rationale behind the decisions.

1.4.1 Design rationale

The design of a new product variant requires understanding the fundamentals and principles of a design and adapting it to new specifications. Thus, reuse of design knowledge from previous design activities could improve engineering design [15]. However, reuse of the design knowledge is plagued with difficulties, including the retrieval and understanding of the prior design [16]. Mostly, the documentation of product knowledge in companies stresses the representation of the artifact, rather than the process of creating it [17]. In such documentation, a developed artifact is usually defined in terms of parameters and specifications to describe the way the artifact works. The documentation, however, does not include the design rationale, that is explaining why the artifact is designed in the way it is [18]. Design rationale provides an insight into the reasons and justifications behind the design decisions [19] which can be used to determine what part of the design can be reused or modified.

The maintenance of design automation systems is essential to retaining their usefulness over time and adapt them to new circumstances. New circumstances could be, for example, the introduction of new product specifications or changes in technology. To maintain a design automation system, frequent updating of the design knowledge (e.g. design rules) is essential. The capture and use of design rationale helps to indicate where changes might be required or how they will affect the system performance [20-23]. Design rationale, by providing a deeper understanding about the design and explaining the reasons behind the decisions, is recognized as an important factor in supporting system maintenance [19, 20]. Thus, providing methods and tools that control and manage design rationale are essential to efficiently maintain the systems [24].
A vast amount of information and knowledge is used and produced throughout the design of a product. The generation of feasible design alternatives requires the effective utilization and application of this information and knowledge [25]. As the design process becomes increasingly knowledge-intensive, the need for methods that effectively enable the capture, representation, share and reuse of product knowledge is necessary [26]. In order to enable reuse, a major problem is identifying which knowledge and information to capture and to what extent, to make the information and knowledge truly useful [25].

1.5 PURPOSE AND RESEARCH QUESTIONS

Due to its potential value, the topic of design rationale has been the focus of research for many years; however, design rationale systems are not in widespread use [27]. The challenges concerning managing design rationale are discussed in literature [18, 19, 27, 28]. One challenge is in capturing and recording design rationale which is mostly realized as a time-consuming and intrusive task. Identifying “what” should be captured, “when” the design rationale should be captured, and “how” the design rationale should be captured are big concerns in managing design rationale. Once the design rationale is captured, another challenge is sharing it with the users to solve similar design problems. An identified issue in the share and retrieval of design rationale is the way the information is structured [29]. Well-structured design rationale aids in the process of sharing it with the users.

It is necessary to recognize that each of these three challenges (capturing, structuring and sharing) are correlated and that the entire process of managing design rationale should be considered. Capturing design rationale without sharing it is useless. It is essential to identify both producers and consumers of design rationale and to capture the design rationale according to the consumers’ needs. Useful structuring supports the documentation of design rationale and makes it easier to retrieve and share it according to the consumers’ demands.

This thesis focuses on the management of design rationale, including capture, structure, and share, that will support the utilization and maintenance of product families and related design automation systems. The research topic is:

Managing the design rationale of a product family in order to support the utilization and maintenance of the product family and related design automation systems

The goals have been to:

- Identify the major stakeholders of the design rationale across the product family’s lifecycle
- Identify the consumers’ needs and capture the design rationale according to that
- Provide solutions to enable sharing the right details of the design rationale according to the current task of the consumer
- Provide solutions for structuring the design rationale
Investigate the challenges in capturing and sharing regarding the type and diversity of the design rationales

Provide solutions to lower the intrusiveness of capturing the design rationale in the design process.

The research questions for this study to support the overall purpose of the research are as follows:

**RQ1. How could the design rationale be captured during the product development process?**

Design rationale capture requires identifying the type of rationale as well as the means and objective for capturing it. This question addresses the requirements for capturing design rationale including the answers to questions such as *What information and knowledge should be captured? Who should capture the design rationale?* and *When should the design rationale be captured?*

**RQ2. How could the design rationale be structured during the product development process?**

This question concerns the structuring and formalization of the design rationale. Structuring the design rationale supports documentation and the process of sharing it with the users.

**RQ3. How could the design rationale be shared during and after the product development process?**

Capturing design rationale without sharing it is meaningless. This question addresses the requirements for making the captured design rationale available for its users. To answer the question, first, the stakeholders of the design rationale should be identified, and then, what information they need and how they would prefer to access that information should be investigated.

When answering these questions, understanding an important term called "traceability", is necessary. Traceability allows following the origin of the knowledge, linking the design decisions to their rationale, and pursuing the downstream effects of the design decisions [30]. Thus, discussions regarding traceability are also provided in this thesis.

This thesis includes seven papers (see the supplements section) that are published or are under the review process over three case studies. Figure 1.1 displays the papers published in each case study and how each paper corresponds to the three research questions. The case studies are discussed in chapter 4. The research was carried out in two case companies that are discussed in section 1.5.
INTENDED INDUSTRIAL AND SCIENTIFIC CONTRIBUTIONS

The industrial contribution of the thesis is to provide means to support the utilization and maintenance of product families and their corresponding design automation systems that are employed to automate time-consuming and repetitive engineering tasks. Such support will make it possible to generate new product variants or modify the existing ones to fulfill new specifications in a short time with minor effort. Methods and principles are provided to enable capturing, structuring, and sharing design rationale across the development process. The practical usefulness of the methods and principles will be demonstrated by prototype systems developed to show the practitioners in the companies how to work with and manage design rationale to support the design of variants.

From a scientific point of view, the intention of this study is to support knowledge modeling including design rationale. Information models are developed to be used as the backbone to form the underlying basis and principles of the design rationale systems. The stakeholders of the design rationale in a product family development process are identified, and scientific methods are used to support collaboration and provide the right detail of information for them.

RESEARCH PROJECTS AND CASE OF APPLICATIONS

The thesis was carried out as a part of two research projects, and the findings were implemented and evaluated in two case companies. Both companies develop and manufacture customized products; however, they differ in types of products and development processes. Developing new design variants according to customer demands is a competitive factor for both. Therefore, the use of design rationale supports the engineers in both companies in understanding the design and responding to customer needs.
1.7.1 Research projects

Adapt project (Strategies for adaptable design automation systems in the manufacturing industry).

The project was a three-year joint project between Jönköping University, the Knowledge Foundation (KK-stiftelsen) and four manufacturing companies.

The overall purpose of the project was to study how design automation systems can be developed in a way that makes it easier to adapt them according to modifications that become necessary over long term use. Two particular aspects were in focus: the management of design knowledge concerning documenting, structuring and validating design rules, and the management of multiple knowledge sources (Meta knowledge).

The research presented in paper 1 was conducted as a part of the Adapt project.

Impact project (Efficient implementation and management of systems for the design and manufacture of custom engineered products).

The project was a three-year joint project between Jönköping University, the Knowledge Foundation (KK-stiftelsen) and four manufacturing companies.

The focus of the project was on the implementation and management of systems for automated design and production preparation of customized products. System implementation concerns the alignment of the systems with other systems and tools in the organizations. System management includes adapting existing systems to changes in product technology, new product knowledge, production practices, new customers, etc.

The research presented in papers 2 through 7 was conducted as a part of the Impact project.

1.7.2 Case companies

Company A. The company follows an engineer-to-order business process and is a supplier of tools for the metal cutting industry. The focus was on the product family development process. During the development process, each product family gets its own defined standard instances like any other product on the market but the process also includes the establishment of design rules to enable generation of new product variants within a so called "design space". Parametric design modules are developed and the design space is governed by a set of design modules and the way these modules are combined. This enables the company to have standard products as well as generate individualized variants within the design space according to the customer demands.

The automation of the design process in the company was started in the early 1980-s and was achieved by developing and implementing advanced rule-based programs, which, at run time, select, modify, and combine design modules based on customer specified input parameters. The output of the automation system is product related information such as 3D models, drawings, selected production unit, NC codes, and measurement instruction.
Company B. The selected company develops and manufactures customized products and accessories, such as roof racks and bike carriers for different car models. The development of a car’s roof rack was selected as a case study. The company acts on the open market competing with car manufacturers and therefore gets no nominal data of car roofs. Instead, the engineers have to collect geometrical information about car roofs by measuring the actual products.

The trend of selling new roof racks is highly related to the time a new car enters the market. Therefore, the company aims to cut the lead time by redesigning and adapting the previously developed solutions to new car models instead of developing new roof racks. For this reason, the company uses a system that allows searching among the existing CAD geometries of roof racks. The system works based on a virtual comparison of the geometry of previously developed roof racks and the new car’s roof geometry in a CAD environment. Based on the similarities in the geometries, the system ranks the roof racks’ CAD models and allows the user to choose those geometries that are more applicable to the car’s roof geometry.

1.8 SCOPE AND DELIMITATION

- This research addresses some parts of the knowledge management concept, such as capture, share, and use of knowledge. Other dimensions of knowledge management, such as human and cultural dimensions, are out of the scope of this research.
- The research addresses “sharing design rationale for users”; however, the psychological issues such as the interpretation of the knowledge by the knowledge receiver, is out of the scope.
- Software applications have been developed to demonstrate the applicability of the proposed solutions. However, the development of the applications is out of the scope of this thesis.

1.9 THEESIS OUTLINE

In chapter 1, the introduction including the background, motivations, problem area and scope of the research, as well as the research questions were presented.

In chapter 2, the applied research method to conduct the study and evaluation of the results are explained.

In chapter 3, the frame of reference and related works are discussed.

In chapter 4, the scientific findings of the research are presented.

In chapter 5, the theoretical results are demonstrated by developing, testing and analyzing the prototype systems.

In chapter 6, the evaluation of the research is presented.

In chapter 7, a discussion of the entire research is presented.

In chapter 8, the conclusion and suggestions for future work are provided.
CHAPTER 2

RESEARCH METHOD

CHAPTER INTRODUCTION

To conduct scientific research, a research methodology is required to explain and guide the process of the selection and application of suitable methods and approaches. This chapter first explains the need and benefits of using a research method for conducting the research in design. Then, the selected method for carrying out this thesis is described. Next, the constructive research and the approach for developing computer based systems, together with a number of factors for evaluation of the research are explained. Finally, the applied research approach is discussed.

2.1 DESIGN RESEARCH

Due to the significant role of design in product development, enhancing the efficiency of design practice is necessary. Improvements in design practice can be achieved by studying design as a topic of research [31]. Research in design is directed at gaining a deeper understanding of design in order to support it through the development of improved methods, techniques or tools [32]. Formulating and validating theories and models about the phenomenon of design as well as developing and validating knowledge, methods, and tools achieved from these theories and models are the two overall objectives of design research [31].

Design science “uses scientific methods to analyze the structure of technical systems and their relationships with the environment” [33]. Research in design aims at improving the design practice, for example, improving product quality or reducing lead time. This requires a model of an existing situation, a vision of the desired situation, and a vision of the support that can change the existing situation into the desired situation [31]. To conduct design research, a design methodology as a “concrete course of action for the design of technical systems that derives its knowledge from design science” and practical experience in different domains is required [33].

2.2 THE DESIGN RESEARCH METHODOLOGY

While a research method assists in making the plans to implement and proceed in the research, it is necessary to consider the chances of achieving valid results. Further, it is necessary to practically deploy and evaluate the results and not just suggest a
solution without evaluation. Taking these aspects into account, to do the research for this thesis, the design research methodology (DRM) framework proposed by Blessing et al. [31] was selected (see Figure 2.1). The methodology is based on four stages:

- **Research Clarification (RC):** In this stage, the researcher reviews the literature to find evidences to support his/her assumptions and formulate a worthwhile and realistic research goal. An initial description of the existing situation and the desired situation is developed.

- **Descriptive Study I (DSI):** This involves determining which factor(s) should be addressed to improve task clarification. The researcher analyzes the literature for more influencing factors to elaborate the initial description. If the researcher doesn't find enough evidence in literature, he/she decides to observe or interview designers at work.

- **Prescriptive Study (PS):** This involves correcting and elaborating the initial description of the desired situation and developing design support by using the identified factors. The description represents the researcher's vision on how addressing the factors would lead to the realization of the desired situation.

- **Descriptive Study II (DSII):** This involves investigating the impact of the support and its ability to realize the desired situation. Empirical studies are undertaken in this stage to evaluate the applicability of the support as well as its usefulness.

![Figure 2.1. The design research methodology [31].](image)

### 2.2.1 Types of research within the DRM method

According to Blessing [31], when using the DRM method, it is not assumed to accomplish all four of these stages or to undertake each stage in equal depth. In some cases, the research focuses on only one or two stages; in other cases, all the steps are carried out. Seven possible types of design research within the DRM framework are listed by Blessing. The list is based on whether the state of the art, with respect to a specific step, requires a comprehensive study or whether a review-based study is sufficient. A review-based study is based on the literature review, whereas a comprehensive study includes a literature review as well as a study in which the
results are produced by the researcher, for instance, an empirical study or developing support. In addition, an initial study, closes the project and aims to show the outcome of the results and prepare the results to be used by others.

A few assumptions form the basis of the selection of these research types as follows (there are some exceptions): each project starts with a research clarification by reviewing the literature, any comprehensive DS-I should be followed by an initial PS to show how the findings could be used to improve design, the comprehensive PS should be based on a review of the descriptive literature (review-based DS-I), and a comprehensive DS-II (evaluation) should be based on the comprehensive PS or review-based PS to identify the background of the support to be evaluated and to indicate how the support is to be improved (Initial PS).

The characteristics of the different types of the DRM are as follows [31]:

Research type 1 (comprehensive study into criteria) is undertaken when the success and measurable success criteria are not well understood. Therefore, a Comprehensive DS-I is required to understand these criteria and their relationships with the problem. The outcome is a better understanding of the success criteria and which metrics can be used.

Research type 2 (comprehensive study of the existing situation) is undertaken when the criteria could be established, but a better understanding of the existing situation is required to identify the factors.

Research type 3 (development of support) is when, based on the literature review and reasoning (Review-based DS-I), the understanding of the existing situation is sufficient to start the development of support.

Research type 4 (comprehensive evaluation) is when support already exists and a comprehensive study (Comprehensive DS-II) is undertaken to evaluate the support.

Research type 5 (development of support based on a comprehensive study of the existing situation), which is a combination of types 2 and 3, undertakes the development of support (Comprehensive PS) based on a comprehensive study of the existing situation (Comprehensive DS-I).

Research type 6 (development of support and comprehensive evaluation), which is a combination of types 3 and 4, undertakes the development of support (Comprehensive PS) based on a sufficient understanding of the existing situation (Review-based DS-I), and the project resources allow evaluation of the support (Comprehensive DS-II).

Research type 7 (complete project) is a project when comprehensive studies are undertaken in each DRM stage.

2.3 CONSTRUCTIVE RESEARCH

The methodology of engineering as a research field is fundamentally constructive [34]. The constructive research is based on the existing, well-understood theories and often starts with empirical investigations. The research process in the constructive approach can be divided into six phases, as follows [35]:

1. Find a practically relevant problem with research potential.
2. Obtain a general and comprehensive understanding of the topic.
3. Innovate, that is construct a solution idea.
4. Demonstrate that the solution works.
5. Show the theoretical connections and the research contribution of the solution concept.
6. Examine the scope of applicability of the solution.

Design research as a part of engineering research involves the analysis of the utilization and performance of design artifacts to understand and improve designed systems. Such artifacts include methods, models, theories, human/computer interfaces, and system design methodologies [36].

2.4 MODELS IN COMPUTER SUPPORTED DESIGN RESEARCH

Having a research approach to present a basis for carrying out the research is essential. Since research in computer-supported design aims to improve the design efficiency by developing computational tools, computer-based studies are linked to the research in engineering design. Duffy et al. [32] presented an approach applicable to design science for developing computer based models. It includes three models such as the phenomena model, information model, and computer model (see figure 2.2). The descriptive models are based upon observation and analysis of the reality of the design and are the basis for the development of information models and, similarly, computational models. The prescriptive models, however, are based on the envisaged (foreseen reality) and to be considered as enhancing the design practice and used to alter, test, and/or optimize the process.

![Figure 2.2. Design modeling research approach according to Duffy et al. [32].](image)

2.5 RESEARCH EVALUATION

The quality of the research shall be evaluated by examining the result and findings with respect to the research questions. In addition, the validity of the research can be verified by determining the truth of the research, whether the applied method is applicable to the problem and acquires what it is intended to acquire, as well as the
truth and accuracy related to the practical employment of the result. The validation of
the research presented in this thesis is carried out by following a number of factors
given by Olesen [37]:

1. **Internal logic** – the result is based on accepted theories, and the work is stringent
   from the problem definition to the result.

2. **Truth** – the theoretical and practical result can be used to explain “real”
   phenomena.

3. **Acceptance** – the theories and results are accepted by other researchers, and
   professionals use tools based on the result.

4. **Applicability** – the use of the tools leads to enhancements, as compared to if they
   were not used.

5. **Novelty value** – new solutions are presented, or new ways of looking at a
   particular problem are introduced.

### 2.6 APPLIED RESEARCH APPROACH

The research procedure is in accordance with the suggested constructive research
process. A problem with research potential is selected. A solution is provided and
demonstrated to show the theoretical connections and research contributions of the
solution. Finally, the applicability of the solution is examined. However, to frame the
complete research work as a whole and carry out the case studies, the DRM method is
used.

As Blessing state [31], DRM is not to be interpreted as a set of steps and supporting
methods to be executed linearly. To proceed the research, many iterations for
increasing the understanding, and parallel execution of stages for a more efficient
process could be part of the reality.

In the beginning of the thesis, a literature study was carried out that aimed to explore
the knowledge gap, realize the desired situation and formulate the required
improvements. The literature review formed the basis for the PhD research proposal
and was also used in the frame of reference for the papers and this thesis. This was in
line with the first stage of the DRM, Research Clarification.

Further, in order to obtain a better understanding of the existing situation from an
industrial standpoint, an empirical investigation was performed through case studies
in industry. The required data regarding understanding the current situation and need
for improvements was collected during open discussions, meetings, workshops and
qualitative interviews with the engineers in the case companies and academic
researchers. Increasing the quality of documents was the identified success criteria.
To improve the identified criteria, three enablers were determined, such as managing
design rationale, including capture, structure, and share; traceability; and the
possibility to define the design space from rules and parametric models. This step
conforms to the second stage of the DRM method, Descriptive Study I.

In the Prescriptive Study stage of the DRM, based on the gained understanding of the
existing situation from the previous stage, the support was developed. At this step,
methods and tools were required to help manage the design rationale. The research
was conducted according to the framework discussed in section 2.4 (the development of computer model). The framework was characterized first by conceptual phenomena models and principles. The phenomena models were the basis for development of the information models. The models are based upon reality and are assumed to evolve since they affect reality when they are adopted. Information models and methods were developed and were used as the basis for developing the prototype systems aiming to evaluate the applicability of the proposed solutions.

Building prototype systems allows the testing and evaluation of the new concepts. The research proceeded to investigate the impact and ability of the prototype systems to realize the desired situation. System evaluations were conducted to appraise the applicability and usefulness of the developed systems and their impact upon the design process when employed. This fits into the fourth stage of the DRM, Descriptive Study II.

Six peer-reviewed and one under-review paper are the results of this research. In figure 2.3, the papers are mapped in relation to the different stages of the DRM. An explanation on the progression of the research by following the DRM method and the way the research design was established for each paper is provided in the following paragraphs.

**Case study 1.** The work was performed in the end of the Adapt project and was based on the research that had been previously conducted in the project in company A.

*Paper 1* is mainly concerned with the PS and DS-II stages in the DRM. The foundation of the paper relies on a literature review that was made by the author of this thesis but was not included in the paper. An information model was presented. Methods and tools were developed and evaluated.

**Case study 2.** Based on the theoretical foundations and results of case study 1, the challenges in the utilization and maintenance of the design automation systems were investigated. A set of qualitative interviews in company B, with three engineers with different roles and years of experience, were performed to formulate the research goal and achieve a better understanding about the situation. The focus was to understand the development process and to learn about the systems, tools and applications that are used by the practitioners and the way these tools and applications are implemented and maintained.

The results of the RC and DS1 stages were used in the first PhD research proposal. Further, a licentiate thesis was written that included the results of case studies 1 and 2, and a seminar with a discussion leader was held in the end of case study 2.

*Paper 2* focuses mainly on the PS stages and to some extent, on the DS-1. An information model was developed to support capturing the design rationale. Wiki was used as a tool to investigate the applicability of the model.

*Paper 3* focuses on the PS stage in the DRM. A method was introduced to support managing design rationale in product design and the wiki-based tool presented in paper 2 was further developed.

*Paper 4* focuses on the PS and DS-II stages in the DRM. The findings from paper 3 were further investigated. The presented method and tool in paper 3 were implemented on a broader scale, and an information model was developed that included product
design and tooling design. The solutions were evaluated by the engineers in company B.

Case study 3. PhD research proposal 1 was updated after the licentiate seminar. The feedback from the seminar was used as input to write PhD research proposal 2.

Paper 5 focuses mainly on the RC and DS-1 stages in the DRM. In order to formulate a clear research goal and focus, and to obtain a better understanding about the situation, a set of qualitative interviews with engineers in company A were performed in two rounds. Three practitioners in the first round and seventeen practitioners in the second round were interviewed. The goal of the first interviews was to understand the development process and to learn about the systems, tools and applications that are used by the practitioners. The practitioners had years of experience and were chosen from different stages of the development process. Based on the information gathered from the first interviews, the second round of interviews was performed in order to study the development process in more detail and identify the stakeholders of the design rationale and their needs. A product family was selected, and practitioners from all the departments who were involved in the process were interviewed.

Paper 6 is a further development of paper 5. The paper concerns mainly the PS stage and to some extent the DS-I in the DRM. In paper 6, a method for capturing design rationale with the focus on two major stakeholders was presented. In addition, questions such as what information should be captured as design rationale, how, when, and by whom were answered in paper 6.

Paper 7 covers the whole result of case study 3 and focuses on the PS and DS-II stages in the DRM. The presented solutions in papers 5 and 6 were further investigated. An information model was developed to support capturing design rationale. The result was evaluated in company A.

The evaluation of the thesis was undertaken by resuming the research questions. Further, the validity of the research, based on the factors explained in section 2.5 was discussed. According to Blessing [31], the research questions, and the available time and resources determine the type of research undertaken. Since prototype systems have been developed and evaluated during the research, it can be stated that the thesis fits into the fifth type of the DRM discussed in section 2.2.1.

Figure 2.3. Mapping the papers in relation to the DRM stages.
CHAPTER INTRODUCTION
This chapter primarily provides an overview of the theories and practices that the research is based on. First, an introduction about the design process is provided. Next, a brief description of the systems for supporting custom-engineered products that explains configuration, knowledge-based engineering, and design automation is given. Then, the basic concepts in design knowledge and design rationale are explained. Further, the fundamental methods and approaches for the capture, structure and share of design rationale are discussed. Next, the research related to this study is presented, and, finally the knowledge gap and motivation for the research are described.

3.1 AREA OF CONTRIBUTION
As the title of the thesis suggests, the research draws inspiration from or contributes to several areas such as design rationale, knowledge management, product development and computer supported engineering design, and design automation. Figure 3.1 positions this research in relation to these areas. The figure is inspired by the Area of Relevance and Contribution diagram (ARC diagram) developed by Blessing and Chakrabarti [31]. The central oval shows the research topic. The circles around the central oval are those areas that are relevant for the research topic in providing background information, theories and models. The circles around each area are the relevant topics within that area.

It is important to consider that this is a rough outline of the area of contribution and that it shows mostly the topics and areas that are of interest or relevant to the research.
3.2 MASS CUSTOMIZATION AND SPECIFICATION PROCESSES

Many companies set their business strategies based on the principles of mass customization to deliver a wide range of products that fulfill customer specifications with the costs associated with mass production. Determining the level of the individualization that characterizes mass-customized products is a major point of contention in mass customization [38]. Four customization levels are identified in [39]: collaborative (holding a dialogue between the customer and customizer), adaptive (altering of standard products by the customer during use), cosmetic (usage of the product presented in different ways for customers), and transparent (adapting the product based on the customer’s needs by the customizer). Understanding the type of customization and its effect on the development and production processes is essential in analyzing the time it takes to set a quotation request and estimate the product price which is vital for firms and, especially for sub-contractors who have to compete with other companies.

It is important for the companies to develop their business models based on the principles of mass customization. Four types of processes for meeting customer specifications exist [40]: select variant, configure to order, modify to order and engineer to order (see Figure 3.2). Select variant is a type of specification process in which a standard product is chosen to fulfill the customer’s needs. Configure to order is a specification process where the standard parts and modules are put together in accordance with a set of predefined rules. According to Havm [41], modify to order or engineer to order processes are suitable when the product is complex or more creativity in design is required. Havm uses the term “creative specification process” for engineer to order and “flexible specification process” for modify to order and claims that the process is engineer-to-order when the product is very complex and a considerable amount of work that involves creativity goes into the design and specification of each individual variant. Modify to order, however, is when the product is less complex and the development of the product takes place based on predefined modules and uses a clear set of rules. The major concern in distinguishing these four
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processes is the “customer order specification decoupling point” that shows at what point the customer needs are considered in the specification process.

Figure 3.2. Different types of specification processes [40].

3.3 DESIGN PROCESS

Engineering design plays an important role in defining the physical form of a product to best meet customer requirements [42]. Engineering design encompasses a wide range of methodological approaches in order to solve different technical problems that require different solution strategies [10]. All the decisions made during this early stage highly affect the product’s cost and development time. At the design phase, customer requirements are investigated and accordingly the most promising solution concepts go forward to the detailed design and development.

Sriram et al. [3] define design as “the process of specifying a description of an artifact that satisfies constraints arising from a number of sources by using diverse sources of knowledge”. Some of the constraints are predefined and form the product design specifications. Hopgood [43] states that the specifications are an expression of the requirements of the product, rather than specifications of the product itself. The latter, which emerges during the design process, is the design and can be interpreted for manufacture or construction, or for allowing predictions about the product’s performance.

Design can also be viewed as a process of solving problems. Hubka et al. [44] describe the design process as consisting of several steps taken toward an optimal product solution. Another view of the design process is specification generation. According to
Ulrich and Eppinger [45] the design process for a customized product is constituted by a description of the specific information processing activities required in the design process. When a new product variant is required, the new specifications are implemented in computer models as input resulting in an adapted product variant as output.

3.4 COMPUTER SUPPORTED ENGINEERING DESIGN SYSTEMS

The computer-based systems applied in engineering design have an important impact on the design process and designers’ activities by influencing the design methods, organizational structures, and division of work between the designers [33]. Many companies use the support of advanced computer-based systems spanning different stages of the development process, from concept creation to detailed design and manufacture, in order to optimize the process and produce products faster and cheaper. The systems are usually a combination of methods and computer technologies that aid in the performance of the design activities. Some contributions in developing computer supported engineering design systems are described below.

Johansson [46] automated the process of analyzing the manufacturability of aluminum profiles. In that work, a method was developed that included the utilization of knowledge objects to synthesize and analyze design proposals, represented as CAD-models and processed to create FEM-models. Using knowledge objects in different steps of the automation process enables building a flexible system of autonomous pieces of automated software in which each knowledge object is implemented for a specific purpose. This makes it possible to focus only on the bottlenecks during the implementation process and run them while further automation is implemented.

Another system is discussed in [47, 48] that supports the designers in searching among the existing product solutions in CAD models and selecting the most applicable one that can be easily adapted to new specifications. The research was extended in a previous study in which the concept of case based reasoning was used [49]. Further, the research was continued and a prototype system was developed to automate the crash simulation of the product variants by integrating the FEA and CAD models [50].

CAD-model parsing for automated design and design evaluation was a research subject for Stolt [51] to reduce the time spent on creating the computer model by reusing the knowledge gained from developing similar products. A computer system embedded in a PLM environment was developed by Mahdjoub et al. [52] to extract and reuse engineering knowledge to improve the efficiency of developing new products. Kanapeckiene et al. [53] developed an integrated knowledge management model by adapting tacit and explicit knowledge for construction projects. The modeling and management of manufacturing requirements in a design automation system was the topic of research by Elgh [54] during the development of an approach to integrate the properties and functions for knowledge execution and information management into one system for car seat heaters. Many additional examples can be found in [24].

There are three main types of systems used for supporting custom engineered products [55], which are based on the configuration of a set of predefined product models and attributes (configuration system), the definition of rules representing engineering the knowledge that operates on a parametric geometry model.
Managing Design Rationale in the Development of Product Families and Related Design Automation Systems

3.4.1 Configuration system

To meet various customers’ requirements, the customized product is designed into parts or modules. Assembling the product would become impracticable by increasing the number of modules and parts. To overcome this issue, a product configuration system can be applied to automatically or interactively configure the product [56]. A configuration system contributes to supporting and integrating the company’s specification activities by modeling the knowledge to enable the definition of all the possible product variants [41]. Cost efficiency, shorter lead time, and quality improvements are discussed in [57] as major benefits of firms conducting a configuration system.

Hvam et al. [41] describe a procedure for designing configuration systems in industrial companies. The procedure involves the analysis and redesign of the business processes that can be supported by a configuration system, the analysis and modeling of the company’s product range, the selection of configuration software, programming the software, and the implementation and further development of the configuration system. The documentation is done by using a product variant master and associated CRC (class relationship collaboration) cards.

3.4.2 Knowledge based engineering (KBE)

KBE studies methodologies and technologies for the capture and reuse of product and process knowledge and aims to reduce the time and cost of the development process by automating the repetitive design tasks [24]. Stokes [4] defines KBE as “the use of advanced software techniques to capture and reuse product and process knowledge in an integrated way”. A more detailed definition for KBE is given in [58] as an engineering method that represents a merging of object-oriented programming, artificial intelligence and computer aided design technologies that benefits customized or variant design automation solutions.

The major benefit of KBE is to save time and cost [24, 59]. Another benefit of KBE is its integrated modeling approach, in which the design knowledge is maintained in a central representation. This allows leverage of a shared knowledge base and offers domain-specific views of a design problem [24]. Stokes [4] further states that adopting KBE might not be suitable when the design process is not clearly defined or consists of creative tasks or when changes constantly occur in technology.

Research in KBE has led to introducing methodologies for supporting the development of KBE systems. The KBE methodologies mainly provide frameworks for formally capturing the design knowledge within a system that can infer and act on the captured knowledge [60]. A well-known methodology in KBE is MOKA (methodology and software tools oriented to knowledge based engineering applications) [4]. MOKA provides a framework for the storage and representation of knowledge in a way that will be useful in a KBE system. MOKA is expressed in accompanying two models: One
is the informal model, which collects the knowledge from experts, documents and
corresponding files in types of illustrations, constraints, activities, rules, and entities. The
other one is a formal model for preparing the knowledge in a form that is suitable for
computer systems and programming. MOKA mainly focuses on “capturing” (collecting
and structuring the knowledge), and “formalizing” (translating the informal model
into a formal model). One of the short comings of MOKA addressed in [61] is that the
general scope of MOKA prevents it from supporting KBE applications being integrated
into multidisciplinary design tasks.

3.4.3 Design tasks automation

Automating the design tasks by means of computer-based tools is a major focus for
research in design automation. The term design automation can refer to: “Engineering
IT-support by implementation of information and knowledge in solutions, tools, or
systems that are pre-planned for reuse and support the progress of the design process”
[5]. The result is mainly an automated process that generates product information as
output [62]. Design automation can be divided into two types [9]: information
handling and knowledge processing. Enabling the reuse of a CAD file is an example of
the former type, and reuse of a spreadsheet for weight calculation is an example of the
latter type.

The benefits of design automation systems implemented in different areas vary
concerning the objectives of the systems, but are mainly connected to shortening lead
time, improving product performance, and ultimately decreasing cost [6]. Further,
design automation systems often facilitate the documentation and maintenance of
corporate knowledge, and enable the designers to focus their work on solving
problems that need skill, experience, and creativity [8].

An important task in the development of a design automation system is the
clarification of the scope and type of the system as well as system implementation.
Cederfeldt [9] defined a set of criteria for system characteristics, among which are
transparency, knowledge accessibility, flexibility, ease of use, and longevity. He states
that the criteria affect system implementation and should be considered for planning
design automation systems. In addition, the importance of the documentation and
maintenance of the system is emphasized by recognizing the need for the versioning,
verification, and traceability of knowledge.

3.5 DESIGN KNOWLEDGE

Before discussing research in design rationale, it is important to understand the
meaning of knowledge and to distinguish among data, information and knowledge.
The following definitions for data, information and knowledge are provided by Turban
and Aronson [63]:

- Data “are a collection of facts, measurement and statistics”,
- Information is the “organized or processed data” and
- Knowledge “is information that is contextual, relevant and actionable.”
They discuss the differences between information and knowledge as: knowledge has strong experiential and reflective elements that can be exercised to solve a problem, whereas having information does not carry the same connotation. A more engineering-oriented definition is given in [64], which states that design knowledge is obtained by the interpretation of information deduced from computational results and factual quantities.

Data, information, and knowledge exist on a wide variety of formats and types across the development process. These may include product information, process information, technology information, tacit knowledge about activities, methodologies, discussions and meetings and catalogued information, assemblies, parts, features, rules, and bill of material. Garcia [65] argues that due to the diversity of information and knowledge needed by an engineering team, in fact, what is data for one person could, in fact, be knowledge or information for others, and so on. Due to this, there has been no sharp distinction between information and knowledge during the conduction of this research, and these terms are used interchangeably in this thesis.

Johansson [66] classified design knowledge into four types in regard to the metalforming industry: 1) heuristic, which is generally found in different handbooks or company standards and is based on skilled engineers’ experiences, 2) analytical, which derives from fundamental physical laws and tends to be more complex than heuristic, 3) numerical which is usually the common method is a finite element, and 4) empirical, which is based on experience. These types could be extended to other industries as well.

3.5.1 Product and process knowledge
Design knowledge can be categorized either as product knowledge or as process knowledge [67]. The former describes the function and behavior of the product, whereas, the latter focuses on the way solutions are created. A more specific definition is given in [68] which states that product knowledge includes the information and knowledge associated to the product, such as relationships between parts and assemblies, requirements, and design rationale. Process knowledge includes the business process knowledge, design process knowledge, and manufacturing process knowledge.

3.5.2 Knowledge base
Having a rich knowledge base about the product and process to quickly analyze and answer a request for a customized product by considering the requirements for design and manufacturing is a big benefit for the firms. The contents of a knowledge base can be used in a number of ways [69]: 1) to disseminate knowledge to other people in an organization, 2) to reuse knowledge in different ways for different purposes, 3) and to use knowledge to develop intelligent systems that can perform complex design tasks.

3.5.3 Managing design knowledge
The ultimate goal of any knowledge management research in engineering design is to reuse the knowledge effectively and efficiently, without imposing too much burden on individuals [67]. Usually, two different lifecycle perspectives need to be considered when addressing the knowledge management and documentation of design
knowledge [70]: 1) Knowledge perspective which includes the adaption of rules and models to changes, for example, new technology, new product knowledge, and new requirements. 2) Product perspective which mainly focuses on methods for generating and managing documentation, version control of rules and models, and the principles of traceability from the product to the underlying knowledge and vice versa.

3.6 TRACEABILITY

Product knowledge includes various pieces of information and knowledge, such as the requirements, relationships between parts and assemblies, geometry, and constraints associated with product and design rationale [64]. An important step toward achieving product knowledge sharing is providing traceability across various product knowledge elements that are used in the design phase [26]. Traceability is important in order to know the origin, relation and sources of the information and knowledge. According to [71], traceability assists in understanding the relationships that exist within and across the product, design, and manufacturing. These relationships help designers ascertain whether and how the design and implementation satisfy the requirements.

Traceability is the key for supporting the ability to follow the origin of the knowledge and pursue affected design aspects, especially when changes occur in design. The information is traceable if one can detect (adapted from [72]):

- The source of the information,
- the reason why the information exists, and
- what other information is related to it or how the information is related to other knowledge.

A product knowledge model was proposed in [26] to support the decision making process during engineering change management and also to enhance the sharing and use of design knowledge during the development process. The focus was on managing traceability across the various product knowledge created during the product development process. Six questions where identified to represent knowledge:

- What product knowledge is created or represented?
- Who are the actors playing roles in creating or using the knowledge?
- Where is the product knowledge created?
- When was the knowledge created or modified?
- Why was certain knowledge created or modified?
- How is the knowledge being created or modified?

Considering these questions along with the previously discussed definitions from Turban and Aronson about information and knowledge and the fact that knowledge is information that is actionable, one can conclude that, usually:

- Information concerns “what”, “who”, “where” and “when” questions.
- Knowledge concerns “how” and “why” questions.
3.7 DESIGN RATIONALE FUNDAMENTALS

Based on its content, design knowledge can be categorized into two groups [55]. One is design definition which describes the results of the design without any explanation concerning the reasons and argumentations behind the design. Such information can more often answer the “what” question. A CAD model, a design table, and a test report are some examples of design definition that are mostly based upon insights, experience, trade-offs, calculation, simulations, etc.

The other one is design rationale which explains the purposes and reasons behind the design in more detail. Design rationale provides a better understanding of a design definition and often aims at explaining the artifact in the way it is designed, answering the “why” question. For instance, “Why does a CAD model look the way it does?”

The definition of design rationale varies and depends on the aim of the design rationale system. The research community has defined design rationale as a way to know the reasons behind a decision [67, 73], but it could also be the justification for it, the design alternatives, and the evaluated trade-offs that led to the decision [19]. In fact, anything in a design process that can be represented and that traces a reason can and should be a part of the design rationale, for example, even the conversations between the engineers during meetings [19].

Most of the design activities during the design process of a customized product depend upon the previous design projects and obtained experiences. In a survey performed by Tang et al. [74], 80% of the respondents said they fail to understand the reason of a design decision without design rationale support. Therefore, it is necessary to capture the design rationale along with capturing the design information [75].

3.7.1 Benefits provided by design rationale systems

Lee [19] points out the potential benefits of using design rationale systems. Some major benefits are listed below:

- Supporting reuse for a better design in the development of a new artifact or modification of existing variants: Reuse can be supported in two ways. One is to serve as an index for similar designs and problems faced. The other is to reuse rationale themselves from past activities to suggest potential design alternatives.

- Support documentation: Design rationale includes explanations of what to do and what not to do. Therefore, design rationale systems support knowledge transfer by learning from the past and explicitly linking the requirements. Moreover, it can be used as an external knowledge repository to support the training of new users and keep them up to date.

- Support collaboration: Implementing a design rationale system is a proper way for designers to share their experiences with other design members.

In addition to the major benefits of design rationale discussed by Lee, Burge [20] mentions three other benefits of using design rationale which are discussed below:

- Design verification: to verify that design meets the requirements.
- Design evaluation: to evaluate design and design choices relative to one another to detect inconsistencies.
Design maintenance: to determine where changes need to be performed to modify the design. Design maintenance includes adaptive maintenance which is the revision and improvement of the usability of the product, and enhancive maintenance, which is the extension on the functionality of the product.

3.7.2 Main steps in most design rationale approaches

According to [27], a design rationale approach should address how to implement three basic processes: 1) how to capture design rationale—the process of extracting design rationale from designers, 2) how to formalize design rationale—the process of transforming design rationale into the desired representation form, and 3) how to share the design rationale—the process of making design rationale available for users. They further discuss the possibility of combining the capture and formalizing processes into a single operation. This is also stated in [76], which defines design rationale capture as a process of recording knowledge as well as organizing the knowledge based on a representation schema, and storing it in a knowledge base. Although both works state the need to formalize and organize the rationale based on representation forms, what is not explicitly mentioned is the importance of structuring the information. Structuring design rationales supports the process of design reasoning by “helping designers track the issues and alternatives being explored and their evaluations” [19]. In fact, there is a trade-off between structuring design rationale and its ease of retrieval. Easier retrieval is achieved with well-structured information.

Capturing, structuring and sharing design rationale are identified as important steps in supporting the management of design rationale in this thesis. The capture and, accordingly, retrieval of design rationale are determined by the representation schema [18], so it is important to select an appropriate representation schema. In order to achieve a better understanding of the available methods and approaches for supporting the capture, structure, and share of design rationale, a literature study has been performed. A brief review is provided in the following sections.

Design rationale capture

During the development process, the designers make thousands of decisions. For example, a module in CAD software could contain hundreds of features, each of which are designed to some extent, to correspond to product functionality and performance. In addition, there are a lot of dependencies between the features, both inside the module and externally with other modules. So, capturing all the reasons behind so many decisions is not efficient and is time consuming. The requirements concerning the scope and the granularity of the design rationale to be captured depend on future needs. These can be difficult to foresee; however, a limitation has to be set as it is not feasible to capture everything during the design process.

Design rationale capture requires identifying the type of rationale as well as the means and objective for capturing it [27]. One suggestion for capturing rationale is to first record as much information as possible during the design process and then organize the rationale based on the representation schema [76]. However, it is not useful when a design rationale system captures and represents every possible detail of the design information. This should always be considered to avoid information overload [18].
Design rationale can be captured in different ways based on the principle of the system. It could be captured during the design phase or when the design process is finished, by the designer directly or by an agent. Regli et al. [18] discuss two major methods for design rationale capture: 1) User-intervention-based capture and 2) automatic rationale capture. User-intervention-based capture is the documentation method created by the designers with the intention to record the history of the design activities as the design process evolves. This type of documentation helps people outside the project to understand the process and activities. Automatic rationale capture records the communication between the involved people to extract design rationale and decisions as they proceed in a design project. A drawback to the automatic rationale capture would be that people might not feel comfortable recording their communication, which would include their e-mails and telephone calls.

The intrusiveness of capturing a design rationale in the design process is a central obstacle for the effective capture of rationale [27] and could be a reason for the designers to avoid it. Such interventions usually use layouts and schemas that define what pieces of knowledge should be captured and how these should be linked together. This requires some extra work from the designers; therefore, design rationale capture might actually be detrimental to a design process and disrupt the designers' thinking. Performing these extra tasks, in addition, is in contrast with what a designer is supposed to do—real design and creativity, not routine and monotonous jobs such as archiving information and documentation.

**Design rationale structure**

Based on a survey of existing and proposed design rationale systems done by the research community, Lee [19] identifies a generic structure for what is being represented by the systems. This structure has three layers: a decision layer containing design alternatives, arguments, and issues; a design artifact layer containing both decision-making steps and related information; and a design intent layer representing information underlying the design decisions, such as objectives and intentions.

In addition, a DSM (design structure matrix) based approach for structuring the system knowledge was presented in [29]. The proposed DSM-based method is a structured way of processing the experience and information obtained from past activities behind the element interactions. The information captured through DSM improves the understanding of the design routes by linking the system elements to the rationales and decisions, which can assist predicting change propagations.

**Design rationale share and retrieve**

The means for internal knowledge reuse in a company was investigated by Stig and Bergsjö [77]. They interviewed a number of engineers with different roles in the company to investigate the challenges associated with accessing and sharing knowledge about technologies. The results of the interviews showed that the means to access the information varies for different engineers. Depending on the phase of the development process, the required information differs from an overview of the knowledge to more details on technologies. In addition, they stress the need for sharing the information in a more professional way, for example, through a forum and
by using systems and tools such as wiki and checklists, instead of using common ways, like sending email or contacting the knowledge producer.

The key to making capture worthwhile and providing requirements for rationale representation is to understand the “use for” or “usefulness of” the rationale [20]. Knowing how the information is to be used brings insight about what information should be captured and how it should be shared. There is a correlation between capturing the rationale and its use. Capturing design rationale will be meaningful only when it is going to be used by people who are interested in it. Thus, it is important to investigate who the stakeholders (users) of design rationale are and what information they need. Identifying the stakeholders is not a big issue, however, identifying what information they need is a challenge. Basically, any design information might be useful someday for the engineers; therefore, it is necessary to identify and capture only the type of rationale that the engineers are most interested in instead of capturing every potential design rationale.

Design rationale systems mostly retrieve the past or existing rationales to solve similar problems. There are different scenarios for retrieving design rationale [18]: to view similar design cases at the initial phases of design, to retrieve rules and criteria to help in making design decisions, or to produce documents after the design process. Depending on whether the user or the system initiates access (user initiative or system initiative) [19], the retrieval of the information can be supported in three ways: retrieval by queries, navigating by the designers, or automatic triggering during the design process that detects certain conditions according to the design context [18].

### 3.7.3 Design rationale representation and approaches

During the design process, the engineer collects and stores a large amount of design knowledge in different knowledge sources. However, providing an appropriate representation that enables access to this vast amount of knowledge, which might differ in type, is a big challenge. The representation formats can be classified into five categories [78]: pictorial (e.g., sketches, drawings, and pictures), symbolic (e.g., decision tables and production rules), linguistic (e.g., verbal and textual communications), virtual (e.g., CAD models and simulations), and algorithmic (e.g., computer algorithms and mathematical equations). In the early stages of design, the presentations are more linguistic and pictorial in nature. During the evolution of the design process, the presentations become predominantly virtual and symbolic [64], though some representations can fit under more than one category.

There are two general methods for representing design rationale: descriptive and prescriptive. The descriptive approach tends to capture the history of the design activities, methods, and strategies. More specifically, what and why and by whom decisions are made [18]. The prescriptive approach aims to improve the reasoning of the designers and attempts to make the design process more correct and consistent [27]. A design rationale approach might be prescriptive in intent but also have some descriptive objectives. Saridakis and Dentsoras [79] discuss computer-based models, which enhance features from the descriptive and the prescriptive models. The computer-based models provide a better understanding of the design problems by addressing the decision-making processes or analyzing the design knowledge.
Tang, et al. [74] discuss template-based and argumentation-based as two methods for representing design rationale. The template-based approach uses standard templates that are incorporated into the design process. The argumentation-based approach uses nodes and links. A node represents a component, while a link represents a relationship between components. This approach is a way to deliberate the reasoning and decisions made during a design process. With the argumentation-based method the designer can trace the decisions and the relationships between the dependencies. The Issue-Based Information System (IBIS) [80], Design Rationale Language (DRL) [81] and Question Option Criteria (QOC) [82] are three well-known approaches in this context. These methods use node elements to represent the design concepts and links to represent the relationships between the nodes. A brief explanation about each method is provided below.

IBIS relies on a problem-solving model that uses cooperatives as an argumentative process. IBIS breaks the design down into Issues. Issues have the form of questions. Positions are the proposed alternative answers to the issues and are evaluated by arguments (both pros and cons). The decision of which Position to accept is called the Resolution. A lot of research has been conducted based on the IBIS method such as [67, 73].

The main components of DRL are the Decision Problem, the Alternative, the Goal, the Claim and the Group. The Decision Problem is something that needs to be discussed and decided. The Alternative is similar to a Position in IBIS. An Alternative can be linked to the Goals and is evaluated by the Claim. An example of a work based on the DRL method can be found in [20].

QOC is used for analyzing and representing the design space around an artifact. Questions are the identified key design issues, Options are the possible answers to the questions, and Criteria are used to assess and compare the Options. An example of a work based on the QOC method can be found in [83].

The differences between IBIS, DRL and QOC are few. According to [27] there are always possible answers (options) for questions in QOC that describe the properties of the designed artifact. The Issues in IBIS include these questions as well as any other question that arises in design. The assessment in QOC, indicates how options perform with respect to criteria. An Argument in IBIS can be used to state assessments. There is no explicit representation of criteria in IBIS. DRL, however, seems to provide a finer level of granularity by answering to a broader range of questions that might arise during various stages of the artifact’s life cycle.

Since there are a few significant differences in these three approaches, Dutoit et al. [27] suggest that it is possible and useful to combine the three schemas according to need.

3.7.4 Review in design rationale methods and tools

Although there has been considerable effort toward developing design rationale systems, we have yet to see the widespread use of representations to facilitate information exchange, especially between knowledge bases and CAD software. One reason is that there are neither appropriate standards available nor widely accessible design knowledge repositories [64]. Therefore, the organizations usually use other
tools and applications for capturing and recording the design information besides the CAD tools. Capturing is effective when it is integrated into the current practices of the actors involved. Lundin [84] states that the capture and representation of design information should derive directly from design implementations and be a natural part of the design process.

To rationalize the design, it is important to understand what type of information and knowledge is used. This has been studied in [85], where the investigations into the nature of rationale show that design rationale includes arguments based upon the following: the philosophy of design, including the process description of the intended system operation; design limitations expressed as range restrictions or environmental factors; factors considered in trade-off decisions such as requirements matching, budget, or timing constraints; technology available to implement and test the design; design goals; and even personal evaluation factors or constraints. Further, it is suggested that the type of rationale that should be captured can be discovered by experiment; observing the engineers—trying to understand the design. The observation can be completed by structured interviews asking about a number of related topics. The knowledge necessary to answer these questions is a requirement for the design rationale capture method. The related topics are, for instance, product structure/model, purpose relative to the intended behavior of the artifacts, supportability of the beliefs used as rationale for the design decisions, the design process (how it was planned and carried out), and design behavior or failure (the what if questions).

Advances in collaborative document repositories enable the organizations to provide tools to support the capture and retrieval of design decisions and their rationales. A knowledge-based tool is introduced in [86] to capture design rationale while making critical decisions in the T-NASA (Taxiway Navigation and Situation Awareness) system in order to support design verification and reuse. Three categories of design knowledge are included in the tool: design driver which refers to high-level design goals and assumptions, design requirement which refers to functional needs and performance requirements, and design elements which refers to the analyzed solution that meets the requirements. The proposed tool allows the designers to capture design drivers and requirements, and map them to design elements. Each element can be related to one or more requirements and each requirement can be satisfied by one or more elements. By adaptation of the QFD (Quality Function Deployment) matrix, the connections between the requirements and elements and why a requirement is satisfied by a particular element are explained.

DRed (Design Rationale Editor) is an IBIS-based tool for capturing design rationale [73]. DRed uses the nodes and links concept and allows engineers to record their rationales as the design process advances and the designers gain understanding of and solve the design problems. An important consideration in designing DRed is that there is no hidden information, everything is displayed directly on the charts rather than pop-up dialogs or windows. Much research has been performed on DRed in order to increase its applicability in the design process. For instance, Bracewell et al. [87] developed an extension to DRed in order to allow a more efficient integration environment. In addition, a software prototype was developed and integrated into DRed by Kim et al. [88] that enables searching the required information according to
the current task of the designer. The proposed solution is an extension to DRed, employing a bidirectional hyperlink approach (tunnel linking) to allow graphs to be distributed over documents and subsequently navigated freely in any direction from any starting point. A bottleneck for DRed would be that by increasing the number of nodes the graphs easily become complex.

The interaction between a design rationale system and organizations’ applications and knowledge sources is an important aspect and should always be considered during developing a design rationale system. A research project demonstrating the feasibility of applying architectural support to manage interaction with heterogeneous information sources was performed in [70]. The focus of the work was on the interaction between the base layer, where the original information resides, and the superimposed layer, where new information or new interpretations are laid over existing information. The aim of the research was to enable the interaction of superimposed applications with base layers using a common interface, regardless of the base layer types or access protocols. In addition, performing navigation and querying with any base layer was also an objective of the research. The findings of the study suggest placing an appropriate application between these layers in order to ease communication between them. Further, an extensible architecture called SPARCE was designed to enable the display of excerpts (formatted exactly or partly as in its base layer) in the superimposed layer. SPARCE provides plug-ins that add a toolbar or menu to Microsoft Excel, Word, and PowerPoint, Adobe Acrobat, Internet Explorer, and Media Player. More specifically, SPARCE applications can provide links to a selection in base documents, for example, in spreadsheets or Word documents [68]. A drawback to SPARCE that could hinder free navigation is that the created hyperlinks to information sources are unidirectional, which means they lead out, but not back in [87].

Developing software tools for annotation has been researched as a means to improve design collaboration. One example is the system developed by Hisarcikililar and Boujut [89] mainly focusing on recording design minutes to support communication in a 3D-CAD environment. Further, Sandberg et al. [90] propose an approach that provides knowledge retention and sharing across the product development process in a CAD environment. The method enables adding design rationale within 3D annotations carried out by designers, allowing design and documentation at the same time. The 3D annotations may include general text notes or hyperlinks to other sources of information such as textual documents, figures, spreadsheets, and URLs. These systems allow the designers to express specific information with a particular intention. In addition, the systems provide an integrated representation of knowledge, awareness of knowledge sources, access to the knowledge and easy communication among system users. However, in both mentioned systems, the applicability of the systems is limited to CAD environments. A solution to improve the situation can be to enable the implementation of more software applications.

3.8 KNOWLEDGE GAP

The potential value of design rationale in the development and maintenance of products is significant, however, the methods and systems developed to record, document, and manage design rationale are not widely used. The capture, structure,
retrieve and share of a design rationale are addressed as major challenges when developing a design rationale system [27, 91, 92]. Looking at the literature, it shows that the research community has addressed these challenges to some extent; however, a knowledge gap has been identified, as follows.

It is necessary to recognize that the capture, structure and share of the design rationale are correlated together and that the entire process of managing the design rationale should be considered. Capturing the design rationale without sharing it is useless. Both producers and consumers of the design rationale should be identified, and the design rationale should be captured according to the consumers’ needs. Structuring supports the documentation of the design rationale and makes it easier to retrieve and share the design rationale according to the consumers’ demands. Looking at the entire process of capture, structure and share, it is essential to consider the users’ acceptance and ease of use. A fundamental problem in the use and retrieval of the design rationale is the diversity of information in type and format. The variety of the applications and software that are used during the design process to use and produce design information should be considered.

To conclude this section, the intrusion on the design process of capturing the design rationale, the interoperation of the system with its external environment and other systems, and the ease of use and understanding for the users are the challenges that need more investigation.

In addition, answers to questions such as What information and knowledge should be captured? When should the design rationale be captured? Who should capture the design rationale? and How should the design rationale be shared for other engineers? are still unclear for many manufacturing companies. These issues have guided the formulation of the research questions in this thesis.
CHAPTER 4

SUPPORTING THE MANAGEMENT OF DESIGN RATIONALE

CHAPTER INTRODUCTION

This chapter summarizes the scientific results. To successfully utilize and maintain the product families and the related design automation systems, use of the design rationale is required. Models, methods, and applications are required to, first, capture and structure the right detail of information and then share the information with the users. This chapter introduces the models and methods; the applications are presented in chapter 5.

Three case studies have been studied in this thesis with (partial or complete) focus on capturing, structuring, and sharing design rationale. Case study 1 is explained in section 4.2, case study 2 is explained in section 4.3, and case study 3 is explained in section 4.4.

4.1 DEVELOPMENT OF SUPPORT FOR MANAGING DESIGN RATIONALE

The realization of principles that support the management of design rationale includes methods and tools to capture, structure, and share information and knowledge across organizations, processes, systems, and products.

During the capture process, the design rationale can be acquired either from communications, for example, meetings and discussions between the design members, or from all proper knowledge sources, for example, documentation and the company’s internal websites.

The next step is to structure the design rationale by formalizing and modeling it and connecting it to the related knowledge sources. This process can be supported by using information models to structure and categorize the design rationales in the right place.

Finally, all the design rationales shall be shared according to the users’ needs. The design rationale can be shared instantly when it is captured or later based on needs. Suitable applications or the design software can be used for the sake of sharing the design rationale.
In this thesis, the processes of capturing and structuring design rationale are integrated into one process.

4.2 INCLUDING DESIGN RATIONALE IN PRODUCT INFORMATION MODELS – CASE STUDY 1

Modeling the product information and knowledge is an important task in the development of a design rationale system. An information model can be developed to form the underlying basis and principles of the system. The information model illustrates the representation of the design knowledge, incorporating both design definition and design rationale. The main focus of design definition is the construction and the results of the design process whereas the main focus of design rationale is the argumentations and supporting descriptions justifying the design.

The focus of study 1 was on the development of product families in case company A. The development process in the company was divided into three sub-processes: product development, engineering design and design programming. Since the documentation of the design information mostly includes the results of the design (design definition), the first step in the project was to provide a model to include design rationale too. A product family was selected in the company, and an information model was developed for modeling the product knowledge. The information model is depicted in figure 4.1 and constitutes a number of specific classes (CAD model, UDF [user defined feature], Rule, Material, Property, Feature, Parameter, and Entity). These classes aim to indicate different types of design knowledge created or utilized during the design process and are tailored according to the specific case study. Commonly, these classes which mostly represent the design definition part of the knowledge, do not explain the reasons or encapsulate the argumentation for their existence. The definitions of such knowledge are mostly based upon insights, experience, trade-offs, calculation, simulations, etc. which constitute another kind of knowledge that can provide a deeper understanding of each class. A deeper understanding can be supported by providing design rationale (the Rationale class) that answers questions such as Why, When, How, Origin, Valid ranges, etc. The answers to these questions can also be supported by access to other sources of related information (the Supporting Object class in figure 4.1). The Rationale class also enables the specification of relations to Rationale classes from PID (product instance description from the product development sub-process) and DMD (design module description). For more details about PID and DMD, please refer to paper 1. Finally, the Item class is the representative of all these classes and provides all the design knowledge regarding a product family, named the product family description (the PFD class in figure 4.1). PFD is a document with the aim of structuring the design information and knowledge (e.g., design rules and modules) that is to be used for communication purposes between the engineering design and design programming and also to provide an overview and understanding of the product family model to support its reuse and maintenance.
The investigations in the project emphasized the importance of design rationale in order to support the utilization and maintenance of product families and their corresponding automation systems. However, there is a need for further studies of supporting methods to enable the process of capturing, structuring, and sharing design rationale. The limitations in the available methods for managing design rationale and the need for improvements were discussed in chapter 3. A solution for reducing the intrusion of the management of design rationale is to embed the capture, structure, and share processes into the current practices of the engineers involved. This can be achieved by providing an integrated design environment in which the tools for capturing, structuring, and sharing the design rationale are the same tools/software that are used by the engineers in the design process. A great advantage of such an environment is that the designers can perform design tasks in different software and applications and concurrently capture and share their rationales. In addition, design rationale can be captured and represented in formats that the designers are already familiar with and would prefer to work with.

In case study 2 a method is developed that integrates the capture, structure, and share processes into the design practice.

### 4.3 Capturing, Structuring and Sharing Design Rationale Across Product Design and Tooling Design – Case Study 2

Figure 4.2 shows how a design rationale system can be introduced to support the decision-making process across the development process. At the beginning of a product development project, there is not much information but a few documents related to the customer specifications and product requirements that are identified in
the project planning phase. Based on the requirements, the engineering design phase is initiated. For many manufacturing companies that develop highly customized products, the engineering process includes the design of the product and the design of the required tooling to manufacture the product. By starting the product design, the number of documents increases rapidly, including test reports, FMEA, and CAD models. Soon, the manufacturing engineers start to develop tooling design suggestions based on the product design proposals. The documents are stored in project file folders, company repositories, or a PLM system and are treated as files. The concepts, ideas and decisions, however, are not stored in single files but are fragmented in many files and have different structures than the file structure or even than the product structure.

As the development process evolves, decisions are made in more detail. Some rationale will be elaborated and some will be modified completely when, for example, a decision made earlier is shown to be incorrect and needs to be altered [93]. The information generated in one phase can be used as input to perform design activities in other development phases. The engineers must be able to, first, record their decisions, intentions, and argumentations and, second, share this information to other design team members. As shown in figure 4.2, the suggestion is to enable the capture and share of the rationale for design members through providing a user interface. Ideally, the user interface is integrated into the current practice of engineers.

The information used, created, or analyzed during a decision-making process is stored in knowledge repositories in the form of test reports, FMEA, CAD models, etc. Beyond that, information such as the intention of activities and argumentations for or against the considered alternatives needs to be captured. Such information should be captured in the design rationale database. A function board links the information stored in the rationale database to the related information in the knowledge repositories (design software) and enables the engineers to capture and share this information through the user interface.

Having instructions for capturing design rationale is required in order to record the right amount of information with the right quality and low intrusion into other design activities. The first step in this research to identify what information should be captured was creating a checklist for capturing the design rationale with the focus on FEA. The checklist that was introduced in paper 3 captures the design rationale associated with the product architecture. The product can be recognized as an assembly constituted of a number of components (which also can be grouped into sub-assemblies in different levels of product structure). So, the checklist describes capturing information in two levels: the component level and the assembly level. Depending on the current task of the designer (designing a component or assembling a number of components together), the design rationale can be captured. Capturing the rationale in the component level includes understanding of the component’s performance and the reasons behind its design, whereas, capturing rationale in assembly level includes an understanding about the interaction of the component with other components in the assembly as well as the assembly’s behavior.
Figure 4.2. Integrating the capture and share of the design rationale into the development process.

Such classification of information prevents capturing duplicate information over and over for each component in one or different assemblies. Therefore, if the component is to be reused in another assembly, there is no need to capture the component's rationale again, since it has already been captured and is a part of the component's knowledge.

The checklist targets two important phases of the development process: the design process and the finite element analysis (FEA). The reason for choosing these two phases was that FEA is mainly the analysis of the design and shows whether the part or assembly works the way it is designed which can steer the designers toward a more cost-effective product. Making a decision in design highly affects FEA and vice versa.

The checklist is described as follows:

1.1) Design rationale capture in component design.
   
   a) The captured design rationale shall explain why the component is designed the way it is. It should also address:
      
      i. Performance of the component.
b) FEM analysis information. Necessary information for finite element analysis of the component.

1.2) Design rationale capture in assembly design.

a) The captured design rationale shall explain why the assembly is designed the way it is. It should also address:
   i. Performance of the component in the assembly
   ii. Performance of the assembly
   iii. Interaction of a component with other components

b) FEM analysis information. Necessary information for finite element analysis of the whole assembly.

According to the checklist, the captured design rationale is mostly an explanation about the component/assembly. The evaluation in the case of company B showed that this type of explanation is helpful. The major benefit of the checklist is to enable the designers and FEA engineers to communicate through capturing and sharing their rationales with each other. An issue is that the checklist is very general regarding what should be captured, which in turn makes the capturing process very individual dependent. Depending on who records the information, it could vary from a short explanation of a component to recording all the decisions taken during the development of that component as well as the interactive design decisions when placing the component in the assembly.

To support the decision-making process during engineering change management and to increase the use of design rationale, a more precise model is required. To achieve that, the product knowledge model explained by Oertani et al. [26] that was discussed in section 3.5 was used. The aim was to consider the six questions (what, who, where, when, why and how) in the design rationale system.

In further research, the results of which were published in paper 4, the design decisions were targeted more specifically. The research covered the whole design process of a product and the design process of the required tooling to manufacture the product. A summary of the research is provided in the following paragraphs.

Figure 4.3 shows a UML model for representing design rationale. The Design Rationale and the Decision classes are central in the model. The design Rationale objects carry general information (text and picture-based descriptions) regarding the concept or idea together with a set of Decision objects. The Decision objects carry information regarding the decisions taken during the design process, such as date, who took the decision and, importantly, the argumentation behind the decision. The Design Rationale objects and the Decision objects have the functionality to produce xhtml-fragments to make flexible web-pages that are generated on demand based on the captured design rationale and underlying information.

The Decision object also contains pointers to the information that the decision and its argumentation was based on. Since that information is scattered, these pointers must
be very specific, yet since that information is of many different types, the pointers must be very general. In the proposed model, pointers to documents that are not related to the CAD models are called Statements. The Statement objects capture information typically found in test-reports, lists of requirements and FMEA documents. (Note that the pointers target sub-sets of the supporting documents, not the whole files.) Since decisions made during the product development process affect the geometry of the product to a great extent, it is possible to make the Decision objects point to the Assembly, Part, Feature, Parameter, and Entity objects in CAD-models. A decision may also affect the material selection of the components of the product or the tooling and in such cases, there are pointers to the Material objects.

The Discipline Model class is introduced to filter the design rationale between disciplines. Product Design and Tooling Design are both derived from the Discipline class in the model presented here, but more such classes could be introduced. A Tooling Design object is associated to at least one product design (which is the common case, but one tool could be used to produce several components). A Product Design object is associated with all that is handed over from the product designers to the manufacturing engineers, including the rationale, as shown in the class diagram (see figure 4.3). When design changes are to be done, the related design rationale can be browsed in generated web pages or accessed through the integrated design rationale environment to see what assemblies, parts, features, parameters, and geometrical entities it will affect in the design itself but also on the tooling. The underlying decisions with all the connected documents will also show up. Going in the other direction that is when changing the tooling design, is also possible when using the proposed class diagram.

Figure 4.4 shows an example of a decision object and how it can be linked to feature and statement classes. A set of headings are defined in the decision class to provide more information about the decision such as date, design members, arguments for and against the alternatives (both selected and rejected ones), etc. The statements and feature can be linked to the decision object but in a more specific way they can be linked to the exact headings in the decision object.

The research was continued in case study 3 with the focus on identifying the stakeholders of the design rationale, both during the development process and after releasing the product to the market and providing models to capture, structure and share information according to the stakeholders’ needs.
Figure 4.3. Class diagram supporting capturing, structuring and sharing design rationale.
4.4 CAPTURING, STRUCTURING, AND SHARING DESIGN RATIONALE FOR A PRODUCT FAMILY SPACE – CASE STUDY 3

The concept of Product Family Description (PFD) was introduced in case study 1. However, issues exist with using the PFD. The biggest issue is updating the PFD during the product family’s Life cycle. When changes are required, the engineers usually perform updates to the final product family model directly in the automation system, not in the PFD. In addition, the primary objective of creating the PFD is for communication between engineering design and design programming. This makes the PFD not suitable for all the stakeholders. To identify the stakeholders and determine what rationale they need, 22 interviews, 11 workshops, and 15 meetings were carried out by the author of this thesis and the engineers in case company A. A product family was selected and one (or several) engineer from each department that was involved in development of that product family were interviewed. The product portfolio manager, product developer, product designer, method developer, design automation engineer, and automation platform developer were interviewed (for more detail, please refer to paper 5). The goal of the interviews was to identify the stakeholders of the design rationale, what information each engineer uses, and what information they create. The results of the interviews showed that the engineers see the importance of the design rationale and acknowledge that it could support them in performing their tasks. However, when they were asked to provide some examples about what types of information are useful for them, the answers were quite broad. For example, one pointed at the need for explaining a parameter in a CAD model, what the parameter does, and how changes in that parameter effect other parameters. One would like to...
have general information about a module, the reasons behind its design and its relations with other modules. One would like to know about the product requirements and product limitations (e.g. constraints in production) and how they affect the product family space.

The examples show how broad the perspectives of the stakeholders are about the design rationale, which makes the design rationale capture even more challenging. This requires capturing a complete history of the design, including all the design activities and decisions and even those decisions that were taken initially but rejected later. As one of the engineers in the company mentioned, allocating the resources to understand, capture, analyze, and maintain the knowledge across the departments requires a big investment. In addition, by capturing so much information and knowledge, there would be a big risk of information overload, which is a bottleneck for rationale retrieval. Thus, it is necessary to find a balance between what is needed and what should be captured.

As a part of the research, the IBIS method was used (see paper 6) on the basis of the work done by Bracewell [73], which targets the design rationale either when a solution is generated, or a problem is to be solved. The suggestion was to capture the history of how a solution was generated or how a problem was solved, and the decisions that were made during these processes. This also includes explaining the strategies or suggestions for solving a problem that arise regularly in development projects. For example, “how to prevent vibration in a milling product during machining?” is an issue that should be addressed in every milling development project. It was suggested to use IBIS-based templates to facilitate the capturing process for such issues.

Figure 4.5 shows how the proposed solution for capturing the design rationale can be implemented in the company’s product family development process. The engineers in product development and engineering design contribute to the creation of the PFD. In addition, they fill in the rationale templates when a decision is made or updated. It is necessary to start capturing the design rationale from the early stages of the development process.

As shown in figure 4.5, in the design programming step, an executable product family model is developed. The PFD is used as the basis for developing the product family model. Ideally, if the PFD is well structured, the design knowledge and design rules can be automatically extracted from the PFD to develop the product family model. By executing the product family model based on customer specifications, unique product variants (within the design space), and corresponding information such as drawings, CMM and CAM instructions are generated automatically. For more details please refer to paper 6.

Although the IBIS method formalizes and structures the design rationale in the form of problems, solutions and arguments, there is still the challenge of the large amount of information and knowledge that should be captured. Recording such a history of solution generation or problem solving requires capturing almost every decision that is made, as well as the analyses of all considered alternatives. Therefore, it is necessary to be more specific about the objective of capturing the design rationale. It is important to identify who is going to use the design rationale and how before capturing it.
To share the design rationale with stakeholders, two aspects of the life cycle of a product family must be considered. First is sharing during the development of the product family, and second is sharing after the product release. The need for design rationale after releasing the product family to the market was a major concern for case company A. Two major stakeholders were identified: product maintenance and special design.

Product maintenance is required when changes occur, for example, when new customer requirements are added, new design solutions are developed, or new technology for production is available. Special design concerns developing tailored instances according to customer specifications that fall outside of the specified valid ranges for the product family but that the customer wants anyway (at several companies, this is referred to as special design).

Special design and product maintenance usually occur after the product release and are often under high time pressure. The engineers need precise information regarding why decisions were made during the development project. Since these departments are not necessarily within the same organization as the product development department, a minimum of information should be provided. Not all of the information regarding the entire product family should be shared with these stakeholders. They would drown in information and the combined information is sensitive and should be considered secret. However, information regarding derived instances from the product family should be shared.

The research was continued by interviewing engineers from special design and product maintenance to investigate what information and knowledge they need (the findings are discussed in paper 7). Understanding how the design space is established was the major concern for almost all the engineers. In other words, they would like to know about those decisions that contributed to defining the design space. This mainly targets the evaluation of the design alternatives and understanding the following question:

**What are the boundaries of the design space, and what constraints contributed to establishing the design space?**
Answering this question requires capturing the design rationale for those design decisions that confine the design space boundaries—the decisions that accept or eliminate a design alternative or a set of alternatives. For example, when the designer decides to set the length of the product to $L \leq 40$ cm, he/she should state why $L=40$ cm is acceptable and what may or may not happen when $L$ is bigger than 40 cm.

The development of the design space in the company is similar to the Set-Based Concurrent Engineering approach [94], where, instead of focusing on one single solution, the engineers consider a set of design alternatives. As the development proceeds, the infeasible design alternatives are eliminated.

Marketing, engineering design and manufacturing are identified as three important criteria sources that contribute to establishing the design space. Marketing concerns the market requirements and customer needs. These requirements create the marketing space, which is about business goals, specifications, and cost for the product family. Product specifications are usually translated into functional requirements that need to be addressed in the artifact. The engineering design space includes all the possible design alternatives that are feasible from the geometric point of view and also meet the functional requirements. So, the engineering design space can act as a constraint to limit or extend the marketing space. It means that there can be some areas in the marketing space that are not functionally or geometrically capable of providing design solutions, or there are design solutions that are beyond the market needs. The manufacturing space, represents an area where any solution within that area is possible to manufacture. Like the engineering design space, the manufacturing space can also limit or extend the other spaces. The design space is the joint area of all three spaces.

To capture the design rationale for the design space, a more expressive method than IBIS is required. It seems that QOC provides a more fine-grained model of argumentation that directly deals with the design space analysis and evaluation of the design alternatives [27]. Thus, the QOC method was used for further investigations.

Figure 4.6 shows the QOC model and the identified sources for criteria. Marketing, engineering design and manufacturing are the criteria sources that contribute to the evaluation of the design alternatives. Since, for the special designers, the focus is only on the evaluation of the design alternatives, the “question” is removed from the QOC’s schema. Positive, Neutral, and Negative are used to weigh the design alternatives. Positive is where the design alternatives meet the criterion, Neutral is when fulfilling the criterion is not necessary from the design perspective, and Negative is when the design alternative does not meet the criterion.

![Figure 4.6. The adapted QOC method.](image-url)
Figure 4.7 shows an information model for capturing design rationale based on the adapted QOC method shown in figure 4.6. The information model is an updated version of a model that was presented in figure 4.3. The model presented in figure 4.7 provides a more structured way of making decisions than the previous model by using the three identified criteria. In this model, design rationale includes the decisions that are made for each design alternative based on the criteria and arguments. This model is to be used as the backbone for developing the design rationale system.

![Information Model Diagram]

**Figure 4.7.** The information model used for developing a design rationale system based on the QOC method.

### 4.4.1 What should be captured as design rationale?

Summing up the results of the research in case study 3 regarding “what should be captured?”, four types of information were identified for the consumers of design rationale across the product life cycle (discussed in papers 6 and 7):

1) The strategies for solving major issues based on the IBIS approach that will most probably raise again in a similar design project

2) The evaluation of design alternatives based on the QOC approach and the identified criteria

3) A description of the core values of the product family, its application area and the possible configuration of parts included in the product family

4) An explanation about the modules in the CAD model including the user parameters, what each parameter does and what the acceptable range for the parameter is and why.
4.4.2 Who should capture the design rationale?

One suggestion is that the designers record design rationale as the design proceeds. However, providing a common language and recording the design rationale in a way that is easy for everyone to understand, requires training and competence.

Another suggestion discussed during the workshops in company A was to use an expert person for the sake of capturing, structuring and sharing the rationale. The expert person should be skilled in modeling design information and knowledge. The expert person shall meet and interview the designers on different occasions and go through the rationale model and complete or modify the model as the design progresses. One advantage of having an expert person is that he/she might ask questions that the designers would not ask each other or that they would consider as obvious for everyone. The disadvantage, of course beside the cost for the company, could be that the expert person might not be aware of the details of design intents.

Since it is the designer who is aware of the design intent, reasons, and downstream effects of his/her decisions, the suggestion is that the designer should be responsible for capturing the design rationale as the design proceeds. This happens currently in the case company, to some extent, in that the designers record their decisions, intentions, and reasons in the form of test reports or technical memos. However, due to the extreme load of information recorded during a development process, after a while, the design rationale is invisible among the documentations. Since design rationale capture might be a time-consuming task for the designers, the use of advanced, computer-based tools, preferably with low intrusion to the design, can assist the designers in design rationale capture. In addition, providing rationale templates as discussed earlier can speed up the capturing process, as the designer only needs to fill in or update the template.

Some issues in capturing design rationale are that the designer might not be skilled in recording the information and knowledge in a way that is easy for others to understand and that the designer might not be sure what information should be captured. Therefore, the expert person is required to guide and instruct the designers, provide a common language among the design team, and go through the rationale model and control it.

For more details regarding this topic, please refer to paper 6.

4.4.3 When should the design rationale be captured?

The author’s experience shows that capturing design rationale in the end of a development project is not an efficient approach. As a part of collecting data for this research, the author tried to capture design rationale for the product case study. The product family had been released one year prior to the study. During several interviews with the product designer, it became clear how difficult it was for the designer to remember what decisions he had made that long ago and why. This suggests that the rationale should be captured, updated, and maintained as soon as a decision is made.

Having defined milestones for where the designers and expert person meet and go through the rationale model can also emphasize and support the capture process. The designers in case company A evaluate their design by making prototypes of the CAD
model (the number of prototypes made during the development of the studied product was approximately 40). The designers usually write a technical report after each test describing the results, progress, issues, and recommendations. This is a document that the designers rely on for making further decisions. So, the suggestion for company A is to use the prototype tests as milestones for when the expert person meets the designers to extract the rationale from the test reports.

4.5 INTEGRATING CAPTURING AND SHARING INTO DESIGN PRACTICES

The sharing of and access to the information is a major point of concern in design rationale systems. A fundamental problem in the share and retrieval of the information is the variety of applications and software used to represent the information. In research that was carried out previously in case company A [95], the documentation and management of product related knowledge was studied. The purpose of the project was to reveal problems related to the reuse of design rules in the company. Investigations in the company showed that it is difficult for individuals to share their well-developed solutions due to not having a system that covered all the organizational tools for such documentation (in that case Microsoft Office programs, CAD, and programming software). Moreover, the difficulty in communication among the design engineers and the design programmers was discussed, and it was stressed that people are, typically, reluctant to add a new application to the tools at hand in order to improve the situation.

Case study 2 has a major focus on the share of design rationale. Since the results of that project are general and can be applied to the other studies as well, this section mainly focuses on the findings from case study 2. A short discussion over the results of case study 3 about sharing design rationale is provided in the end of this section.

Capturing and sharing are two processes that must be coherently aligned. To ensure that, the suggestion is to make the sharing process be the capturing process itself, that is, make the engineers communicate through the capturing system. As shown in figure 4.2, as soon as a design rationale is captured, it is shared with the other design members. Integrating the capture and share into the design practices reduces the intrusion of these processes into design. Access to the information can be strengthened by allowing the user to browse and navigate across the documents containing the design rationale. A common user interface can be provided in each type of software to share all the rationales, statements, and decisions. Hence, the suggestion is developing add-ins to the targeted software applications in a standardized way so that the users feel comfortable and recognize the system and the functions it stands for.

In the standardized add-in user interface, there should be functionality not only for monitoring the available design rationales but also for connecting the related statements (as discussed in figure 4.3). The user interface can facilitate the user in creating a new design rationale, connecting the statements together, and documenting the decision. Since the user interface is common for all the software and controlled by the function board, whenever a new design rationale is captured or a new link between the statements is created, all the activities are presented, and the content of the windows is updated simultaneously in all the software. An example of how the user
interface could look is presented in figure 4.8. More details can be found in papers 3 and 4.

Figure 4.8. Enabling the capture and share of design rationale via a common user interface.

A database that keeps track of all the design rationale can be used. The design rationale system could be implemented either as local installations on the engineers’ desktop and laptop computers but would most preferably be installed as a centralized system on a server like a cloud solution (see figure 4.9). In the former case, the design rationale is used by engineers like local scrapbooks for keeping a record of their own thoughts and connections, which represent the engineers’ individual knowledge about the product. In the latter case, the design rationale is stored on the extended enterprise central server (in the cloud). It is then also possible to interactively communicate selections of design rationale to other users in real-time across the globe. More details about the cloud solution are described in [96].
How the design rationale is shared depends on what the user prefers. It can either be presented directly in the CAD software in the form of comments or annotations, in a spreadsheet with predefined templates, or in the form of an electronic book. These solutions have been tested in case study 3, and the results were published in paper 7. Two types of sharing were provided: active share and passive share. Active share is when the rationale is shared with the stakeholders according to their current design activity. For example, when a designer wants to change a parameter in the CAD environment, the design rationale for that parameter is accessible through the CAD software in the form of comments, tables and pictures. Passive share is a package of the required rationale about a product family for a specific stakeholder (e.g., in form of PDFs or e-books) when the product family is released to the market.

4.6 SUMMARY OF THIS CHAPTER

The importance of including design rationale in product information models was emphasized in case study 1. An information model (presented in figure 4.1) was developed to include design rationale in the product information. To support the understanding of the different classes in the information model, design rationale was expressed as argumentations behind the design decisions linked to each class. However, the design decisions were not clearly stated in the information model. The information model, in addition, expresses the diversity of the design information and emphasizes the need for providing suitable methods and tools to capture and share design rationale in different formats.

The research was continued in case study 2 by providing a method for capturing, structuring, and sharing design rationale. The focus was on targeting the diversity of design rationale. This requires an understanding of what types of design rationale exist and the major sources from which the design rationale can be captured. The suggestion was to provide an integrated environment comprised of common design software to enable capturing and sharing design decisions and their rationale in suitable formats during the design practices. An information model (presented in figure 4.3) was developed to support capturing the design decisions in product design or tooling design disciplines. Each decision is expressed by the date the decision was made, the person who was responsible for the decision and an argumentation for that decision. A decision can target an assembly, a part, a feature, a parameter, an entity, or
the material in the geometrical model of the product. More details about the decision are accessible through the provided links to the supporting documents, called statements in figure 4.3.

Although a number of headings were provided in the decision class (shown in figure 4.4) to support the engineers in documenting the decisions, there was still a need for an approach to provide a common base for capturing design rationale. It is necessary to first identify what information should be captured and then document the information in a way that is easy for others to understand. This was further studied in case study 3, where the argumentation-based approaches, such as IBIS and QOC, were used to categorize the information in the form of issues, solutions, arguments, etc. To decide “what should be captured?”, the stakeholders of the design rationale and their needs were identified. Four types of information were recognized as major points of interest for all consumers during the product life cycle but mostly for the aftermarket consumers. Design rationale was captured with the focus on the aftermarket consumers by including templates in the argumentation-based approaches. An information model was developed to support capturing those decisions that deal with evaluating design alternatives based on the QOC approach. In addition, questions such as Who should capture the design rationale? and When should the design rationale be captured? were addressed in case study 3.

A comparison between the three case studies is provided in table 4.1. The representation of design rationale, whether it is descriptive or prescriptive, the approaches, whether they are argumentation-based or template-based, the information models, whether the decisions are expressed explicitly, the way the design rationale is expressed, and the consumers of the design rationale are compared.

<table>
<thead>
<tr>
<th>Representation of design rationale: Prescriptive vs Descriptive</th>
<th>Case study 1</th>
<th>Case study 2</th>
<th>Case study 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Descriptive</td>
<td>Descriptive</td>
<td>Descriptive</td>
<td>Descriptive in intent but also has some prescriptive objectives (by capturing the strategies for solving problems)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Argumentation-based vs template-based</th>
<th>Template-based</th>
<th>Template-based</th>
<th>A combination of template-based and argumentation-based</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(but also inspired from the IBIS method)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Decisions                                                     | Not explicitly expressed in the information model | Explicitly expressed in the information model | Explicitly expressed in the information model |

<table>
<thead>
<tr>
<th>Design rationale is expressed in form of:</th>
<th>1. Argumentations behind design decisions</th>
<th>1. Argumentations behind design decisions</th>
<th>1. The strategies for solving major issues based on IBIS approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional information to be captured:</td>
<td></td>
<td></td>
<td>2. The evaluation of design alternatives based on QOC approach</td>
</tr>
<tr>
<td>• Explaining the decision</td>
<td></td>
<td></td>
<td>3. A description of the core values of the product</td>
</tr>
<tr>
<td>• Date of making the decision</td>
<td></td>
<td></td>
<td>4. An explanation of the important parameters in the CAD model</td>
</tr>
<tr>
<td>• The decision maker</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Additional information to be captured:
- Date of making the decision
- The decision maker
- Design alternatives
- Evaluation of the design alternatives against the criteria

| Producers of design rationale | Product developer and designer | Product designer and tooling designer | Mainly: product developer and designer
|                              |                                |                                    | Potentially: production, product maintenance and special design

| Consumers of design rationale | Is useful for product maintenance | Is useful for product maintenance and production | Is useful for production, product maintenance and special designers |
CHAPTER 5

PROTOTYPE SYSTEMS

CHAPTER INTRODUCTION

In chapter 4, the models and principles for the management of design rationale and support for the utilization and maintenance of product families and their corresponding design automation systems were introduced. The findings have been investigated and examined by developing prototype systems in the case companies. The developed prototype systems in case studies 1, 2, and 3 are described in sections 5.1, 5.2, and 5.3.

5.1 INCLUDING DESIGN RATIONALE IN PRODUCT INFORMATION MODELS – CASE STUDY 1

The study was a part of the Adapt project described in section 1.5, and the case company was company A.

5.1.1 The development process in the case company

A new product development project is initiated based on market insight or technology insight. The product developer gets a list of demands for the product and starts the design process of representative instances, a work that includes many iterations and tests. The design information and knowledge is, to some degree, captured and documented by the engineers, but most of the documentations are test reports. When a set of instances are developed (some variants in the extreme points of the design space are defined), geometrical rules and models are defined by the designers so that any instance of the product within the space of the product family can be represented. The output from engineering design contains rules and parametric CAD models, which, subsequently are submitted to the design automation department. The information from engineering design is then used by the design automation programmers to build a generic model that includes executable computer programs that generate variants of the product within its space.

5.1.2 Project description

The main objective of case study I was to develop, implement, and evaluate a system foundation for the modeling and management of product knowledge supporting the reuse, expansion, and maintenance of product families and their corresponding design automation systems. The “Descriptions” were one of the central parts of the proposed solution for knowledge modeling. The content of a Description includes, for example,
an explanation of the overall product, assemblies, parts, rules, and parameters. This constitutes the design definition of a Description. By adding information and links concerning aspects such as calculations, analyses, and constraints, as well as the reasons and argumentations behind the design activities, the design rationale of a Description is completed. In order to fill out the Descriptions, templates were used to support high-quality documentation.

Three different Descriptions related to the three development sub-processes in the company were introduced to support capturing the design definition and design rationale and to enable traceability across the whole development process.

The focus of the case study was on the engineering design sub-process. A Description called “Product Family Description (PFD)” was created for this sub-process. This description is to be used for developing the product family model. The basis of the PFD relies on an information model (the information model is the one presented in figure 4.1). A milling product was selected and a pilot system was developed based on the presented model for the documentation of the product family.

5.1.3 Prototype system

A semantic wiki was used as an application to demonstrate the applicability of the PFD. Wiki is a type of content management tool and enables linking, navigating, and searching information. It allows the users to edit and form both the information and the structure to fit their purposes in an organic way. Free available sources and user friendliness are the other benefits of using wikis.

The PFD was described by linking to a number of articles (pages created in the wiki). Each article corresponds to a part in the product architecture. The documentation of the information and knowledge relevant for the part was placed within the page. Both the design definition and design rationale were captured. Since the current documentation at the company focuses mostly on the design definition without recording the design rationale, the argumentations and reasons behind the rules, geometries, etc., were extracted from the designers during several meetings and discussions. The information and knowledge was described explicitly by using text, figures, tables, and rules. In addition, the supporting documents, such as Excel and Word files, were uploaded in the relevant pages. Figure 5.1 shows the main page of the PFD described by linking to a number of articles.

5.1.4 Analysis of the prototype system

The usefulness of the information model and the provided solutions were confirmed by the company representatives in general which indicates the applicability of such an information model in the development environment. The need for further investigations and supporting tools for efficiently feeding the systems with the right amount and quality of knowledge was also stressed.
User acceptance was found to be an important factor in the case study to successfully implement and manage a system. It is strongly related to the access to and understanding of the knowledge. The diversity of the design rationale, the need to represent it in different types and formats, and the need for a method to allow capturing and sharing it in different types and formats according to the system requirements and user preferences were emphasized.

The selected tool, wiki, is a text-based application that has limitations and cannot be a perfect solution on its own. Therefore, there is a need to implement other tools and applications that allow capturing and representing the knowledge in a wider range of formats.

The findings from case study 1 formed the basis for further investigations in case study 2 and the development of a prototype system that manages and controls the design rationale.

### 5.2 Capturing, Structuring and Sharing Design Rationale Across Product Design and Tooling Design – Case Study 2

The study was a part of the Impact project and the company was company B.

#### 5.2.1 The development process in the case company

The development process of the roof racks was selected for further investigations in the company. A clamping roof rack is a rack used on cars without rails on the roof (i.e. the rack is standing on the roof and clamped around it where the doors are). Figure 5.2 shows how a roof rack is attached to a car. The roof rack is developed in a way that enables the engineers, to instead of developing a complete new roof rack for a new car, only design the two components called brackets and footpads and adapt the roof rack to the new car accordingly.
5.2.2 Project description

First, the research aimed to identify the major issues when a design automation system is implemented in a company. Next, a prototype system was developed to solve the identified issues and enable the capture, structure, and share of the design rationale.

One of the identified issues was organization, concerning the alignment of the system with other systems and its external environment, as well as communication and collaboration among system users. It was stressed that considering organizational aspects during the development of a system facilitates its implementation and integration within the organization.

The other issue which was the central of focus in paper 2, was the documentation concerning the management and modeling of product knowledge during the development process. Similar to case study 1, when studying the documentation of product knowledge at company B, it was concluded that it is mainly directed toward describing the final results of different design activities. Such information might be enough if the content of the system (e.g., rules) is to be used as it is. But if the design is modified or the rules are changed, more information explaining the reasons behind the design activities is required. In order to solve this problem, the study provided a solution for the documentation required for the design automation system.

5.2.3 Prototype system

To provide a model to represent the required information for the automation system, an information model was developed. The information model is presented in figure 5.3. In this case, a wiki solution was also created to present the model to the engineers at the case company (see figure 5.4). More details can be found in the appended paper 2.
Figure 5.3. Information model incorporating both design definition and design rationale.

Figure 5.4. Main page of the prototype system created in wiki.
To overcome the identified issues discussed in section 5.1, a more precise system than a wiki is required. The need to provide a tool integrated into the design software that allows the capture, structure, and share of the design rationale in a simple way was stressed in chapter 2. A prototype system that integrated SolidWorks, Word, Excel, and wiki pages was developed to evaluate the model introduced in section 4.3. The system was coded in a VB.net environment and could be installed as an extension in Word, Excel, SolidWorks, and a web browser to provide the same functionality for the wiki.

The reason for choosing different software was to enable the capture and share of the design rationale in different formats. SolidWorks was chosen as the representative for 3D modeling, Microsoft Excel for rules definition and drawing tables, and Microsoft Word for textual usage. Besides the software, wiki pages were chosen to record the decisions. In this project, 18 wiki pages were created that explained several decisions.

An information model, displayed in figure 5.5, was developed in order to form the principles of the introduced method. The information model consists of two types of classes: general and specific. The general classes comprise Design Rationale, Decision, and Statement classes. The Statement class includes any of the software applications. The specific classes target the software applications, in this case Word, Excel, and SolidWorks. It is possible to extend the information model to target other software applications by implementing new types of specific classes, indicated with dashed lines in Figure 5.5.

When using the information model, the statement class carries information about where the actual design content is stored. These statements can be viewed as hyperlinks, which can point to a specific file on the hard drive or a web-page at a certain URL, but the statements are more specific than that and point to, for instance, a specific feature or a dimension in SolidWorks, a specific bookmark in a word processing document, or a certain range of cells in Excel. Additionally, the decision class is used to cluster the statement objects that are related together. For example, some ranges of spread sheets, bookmarks in different textual documents, and some features in some geometrical models that have something to do with each other in a natural way can form a decision class. Such a group can be viewed and utilized as a multilateral hyperlink that makes it possible to go back and forth from one statement object to several others. So, for instance, when selecting a feature in a CAD model that is targeted in a statement class, all other statement objects in that decision can be monitored by the user, making it possible to jump to the connected workbook or spreadsheet entities, or other 3D-modeling entities.

To make the decision classes meaningful, they are stored in Design Rationale objects that can contain a number of decisions that are somehow naturally connected to each other.

It should be considered that the information model for the developed prototype is slightly different from the UML model presented in figure 4.3. Here, the geometrical model class is included in the statement class.
Use case example

In order to express the functionality of the prototype system, an object diagram was created by showing two examples of decisions made in product and tooling design (see figure 5.6). Decision 1 is about changing the dimension of the footpad after testing the created prototype. This decision includes one statement recorded in FMEA and one statement recorded in the CAD model. Decision 2 concerns applying changes in tooling design after changes occur in the footpad design. This model is explained in the following sub-sections. Due to the company’s policy, the information presented in pictures 5.6–5.12 is fictive.

Figure 5.6. An object diagram illustrating two examples of decisions in product design and tooling design.
Product Design:
The graphical user interface of the prototype system consists of three windows (task panes) added to each targeted software application (shown in figures 5.8 and 5.9). Two windows, called Design Rationales and Statements, are added to the right side of each type of software. The third window is named Decision, which is shown at the bottom of the software. The properties of each window can be summarized as below:

The Design Rationale window edits and monitors all the design rationales regardless of which software they were first created in. This window shows the created design rationale and is constituted of two tabs named Active Selection and Browse. The Active Selection tab enables adding, editing, or removing a design rationale. It is also possible to attach an extra file, for instance a wiki page, to a design rationale. All these functions can be accessed by right clicking in the windows and selecting the desired function. The Browse tab monitors all the available design rationales.

The Statements window allows to link the related statements together by forming groups. This window provides functionality to group the related statements together across different software.

The Decision window displays the decision (wiki page) attached to a design rationale.

An example is given here to show how product designers are to work with the suggested system. This example targets the design process of the footpad. According to the requirements, two design alternatives are considered, and after some evaluations, a decision is made on choosing one of the alternatives. A prototype of the selected alternative is created. The prototype is tested, which indicates the need for performing some changes in the footpad design.

Figure 5.7 shows the created wiki page explaining the decision. It should be considered that this wiki is a sub-page of another page that provides an explanation in a higher level of granularity about the product. A template that includes some headings is provided to make it easy to record, understand, and modify the content. The headings are: article name/number, design date, design team members, intention and goals, assumptions, alternatives, and evaluations. As seen in figure 5.7, the page is not only to address the decision that led to the final solution but also explains how the decision was made and analyzed, whether there were other alternatives considered but rejected, and how the alternatives were evaluated. The evaluation section explains that the final design of the footpad was tested by making a prototype, but, it has been difficult to mount the prototype on the car. This can happen due to the level of accuracy in the manufacturing equipment. After a discussion between the product designer and the tooling designer, the designers agreed upon changing the tolerance to 1.

The change of the rectangle’s dimension should be applied in the footpad CAD model. Figure 5.8 shows the footpad designed in SolidWorks. First, the corresponding feature for the big rectangles in the tree view in SolidWorks is selected. Next, a design rationale object called “design of big rectangles” is created by right clicking in the active selection window. By creating a design rationale instance, the statements window is updated, showing the path for the feature in SolidWorks. The user can assign a name to the decision, for instance, prototype evaluation in the statements window, indicating that this group of statements addresses a decision regarding the prototype evaluation. This allows the user to categorize the statements that address the same
Moreover, the user can assign a particular wiki page or even a PDF file as an attachment to the design rationale (shown in active selection window). In this example, the wiki shown in figure 5.7 is attached to "design of big rectangles".

![Figure 5.7. A decision in footpad design recorded in wiki page.](image)

In addition, the change of the dimension in the footpad design should be captured in FMEA. Figure 5.9 shows a statement in the FMEA captured in Excel that targets certain cells addressing this issue. Since both SolidWorks and Excel are controlled by the function board, the content of the user interface in Excel was updated when the "design of big rectangles" was created in SolidWorks. Now, the user can select the corresponding cells in Excel, right click on the prototype evaluation in the statements window and click on "add statement". The statements window will be updated to show paths to two statements. So, a design rationale object is created called "design of big rectangles" that targets two statements: one a feature in SolidWorks, and one a range of cells in FMEA. The statements are now connected to each other, which means that if the user clicks on the rectangles in SolidWorks, the corresponding cells in Excel document will be highlighted in blue and vice versa, by clicking on a cell in that row in
the Excel the rectangles in SolidWorks will be highlighted. This makes it easier for the users to find the particular statement that they are looking for that is linked to the current statement they are clicking on.

The wiki page that was attached to “design of big rectangles” is also shown in the decision window in figure 5.9. It can be maximized or opened separately if it is preferred.

Figure 5.8. The Footpad modeled in SolidWorks.

Figure 5.9. The FMEA recorded in Excel.
Tooling Design:

Decision 2 shown in figure 5.6 is explained in this section. The main process in manufacturing a footpad is using a press machine. A tooling is to be developed to be used in the press machine for forming the footpad. The tooling consists of plates and cylinders that are designed separately and then assembled together. The design team agreed upon the reuse of a tooling that was developed previously for manufacturing a former footpad variant. Figure 5.10 shows the wiki page created to record the decision. The page was created by following the same template as used in product design.

Due to the changes in the footpad design, the tooling needs to be modified. Two alternatives are considered, and after a discussion, the second alternative, which suggests changing the positions of the cylinders in the upper plate, is chosen. The arguments for and against each alternative are recorded in the wiki.

When the decision is made, the changes should be performed in the CAD model. Figure 5.11 shows the tooling modeled in SolidWorks. The upper plate is indicated by an arrow. The upper plate’s sketch is modified according to the decision, and a design rationale object is created called “upper plate targeting the new dimension”.

Further, the change is recorded in the design memo in order to inform the other engineers. Figure 5.12 shows the design memo recorded in a Word document. By opening up the document, all the created design rationales are shown in the user interface. Now, the user can select the lines that express the change, select the upper plate in the design rationales window, right click on the corresponding file path, and select “add statement”. The dimension in SolidWorks is connected to the lines in Word. By clicking on the lines in Word, the plate in SolidWorks will be highlighted, or vice versa (some lines in Word are highlighted in gray in figure 5.12).

The wiki page containing the information about the decision is also attached to the upper plate, shown in the decision window.

The system allows the users to group a number of design rationales together by mapping them into a virtual folder. For instance, Tooling is a folder containing three design rationales such as upper plate, press, and cylinder (see the Browse tab in figure 5.12).

5.2.1 Analysis of the prototype system

The prototype system of integrating SolidWorks, MS-Excel, MS-Word, and Wiki was developed to examine the applicability of the proposed model for managing design rationale. The aim was to choose some of the common and popular design software. Microsoft Office tools are broadly used in many organizations and can be used as knowledge repositories in different formats. SolidWorks is a powerful and common CAD software. A discussion about wikis is provided in the end of this sub-section.
Managing Design Rationale in the Development of Product Families and Related Design Automation Systems

Figure 5.10. A decision in tooling design recorded in wiki page.

Figure 5.11. The tooling modeled in SolidWorks.
All the design rationales and statements are presented in each application, regardless of which application they were first created in. Since the user interface is common for all the software, whenever a new design rationale is created, all the activities are presented, and the content of the windows is updated simultaneously in all software.

The system was tested through a design automation system where a focus was set on the need to share knowledge between FEA and product design (discussed in paper 3). The system was also tested across product design and tooling design processes due to the significant need for information exchange and collaboration among the involved design teams when developing custom engineering products (discussed in paper 4). The findings have made it clear that the introduced system is capable of facilitating the information exchange and navigation of the design rationale across the development process of customized products.

So far, the system is implemented as a local installation on users’ computers but in order to evaluate the functionality of the system, it must be centralized on a server to be used by a group of users. In such a scenario, a database is required to facilitate communication among the knowledge sources, and an editor is required to efficiently manage and edit the created design rationales.

Wiki applications were used as a part of the developed systems during the research. Wikis can be used to manage engineering knowledge and are usable for capturing knowledge across individuals [97] in the form of web pages. However, a wiki has more applicability and differs from a website or a blog. Wiki is a type of content management tool and enables linking, navigating and searching the information. It allows the users to edit and form both the information and the structure to fit their purposes in an organic way. A big characteristic of wiki is to involve the user in an ongoing process of
creation, collaboration, and modification of the webpages. Although the ability of every user to be an author and editor allows the user to contribute in a flexible way, it also makes wikis susceptible. There is always a large potential for misinformation because there is no system to validate the information that someone might put on a wiki page \[98\]. This could be more obvious, especially in large wikis, where a lot of members are involved. However, in many wikis, it is possible to edit the security features in order to restrict information access or limit editing privileges to only certain individuals. In other words, wikis have great benefits but are not perfect. Currently, different wiki software is available to serve different purposes. Further, it is possible to install extensions on wikis to improve their performances.

5.3 CAPTURING, STRUCTURING AND SHARING DESIGN RATIONALE FOR A PRODUCT FAMILY SPACE – CASE STUDY 3

The study was a part of the Impact project and the company was company A.

5.3.1 Project description

The project was based on the findings from case study 1. The first step of the project was to identify the stakeholders of the PFD. To identify that, a set of interviews was carried out with the engineers from different departments in the company (see paper 5). During the interviews, the engineers were asked to describe their tasks in the development project. In addition, they were expected to answer a number of questions about the PFD, for instance, whether they use the PFD (partially or completely), how often they use it, and if it helps them in performing their engineering tasks.

Table 5.1 shows how the stakeholders contribute to creating or using the PFD. The designer is the one who contributes to creating the PFD. The PFD is mainly used by the automation and product maintenance engineers. In this particular case, the designer of the product was also responsible for its maintenance. The production engineers are not so keen to use the PFD. They would prefer to have all their required information available in the CAD model or linked to it. When it comes to the special designers, they stressed that, most of the time, they do not have access to design documentations. The only sources of information that help them to understand the family range and design space are a product configurator program that is used by salespersons and product catalogues, including the standard articles. This lack of information sometimes leads to declining a customer request.

In order to explore the usefulness of rationale in the company, the engineers were asked to provide some examples of problems that they currently face and which access to rationale would support them in solving. Below is a list of some questions that were addressed by practitioners.

Table 5.1. The PFD and its stakeholders.

<table>
<thead>
<tr>
<th>Stakeholders of PFD</th>
<th>Designer</th>
<th>Design automation</th>
<th>Production preparation</th>
<th>Product maintenance</th>
<th>Special design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Create</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Use</td>
<td>X</td>
<td>X</td>
<td>(barely use)</td>
<td>X</td>
<td>-</td>
</tr>
</tbody>
</table>
Managing Design Rationale in the Development of Product Families and Related Design Automation Systems

- Who is the responsible designer?
- What is the impact of this change in design?
- Why does this parameter have this value?
- Why has this design alternative been selected?
- Are particular design alternatives associated with certain zones in the design space?
- What are the product limitations? What is possible or not possible at all?
- Why are these min/max values set for this parameter?
- Is this the latest version of the document?

Answers to some of these questions can be obtained from technical and prototype test reports that are recorded in the company's database. However, due to the difficulty of access or not being aware of the existence of such information, they are rarely retrieved.

5.3.2 Prototype system

During the development process, support is required to define and model the product family, which is developed gradually from creating some product instances to specifying the whole design space. It is required to capture the design rationale during the process which in the end it is included in the final product model. The final product model contains design rules, geometric models, and design rationale.

IBIS, as an approach, and a software called MindManager [94], as an application, were used to capture the design rationale (see figure 5.13). The software is a mind mapping tool that enables the organization of ideas and information. The example presented in figure 5.13 is a simplified example, and just some relevant arguments and comments are presented. An issue was raised in the design of a milling product (how to ensure strength in the product). Two options that can affect the strength were identified by the designers. One was the size of the screw in the insert, and the other one was the distance between the inserts in the cutter body. The example focuses on the design of the cutter body and the distance between the inserts, which is affected by other parameters, such as the number of inserts, the design of the inserts, the chip material, and the design of the Chip space. The options, issues, and arguments about the Chip space were captured. Some changes in the design of the Chip space were performed, and a prototype was made. The results of the prototype test were captured, and the arguments were written. The prototype was modified and tested again. Finally, the results met the requirements. “P” in figure 5.13 refers to the parameters in the Chip space module in the CAD model.
Using templates for capturing design rationale

The company develops different types of products (e.g. milling, turning, and drilling). The product structure is basically the same within each type of product and is constituted by several pre-developed modules. For example, every milling product has a body, insert, insert screw, coupling, etc. Since it is a parametric design, the modules are flexible in size and can be reused in every new development project. So, when there is a new development project, the designers have good knowledge about the product.
structure, what modules are going to be used, and what issues and problems need to be solved based on experiences from previous projects. Issues such as:

- how to ensure strength in the product?
- how to prevent vibration in the product?
- what is the minimum amount of required material between the insert seats? and
- what is the relation between the Chip space dimensions and type of material to be machined?

are issues that rise up in every milling development project. Although the answers to these issues might differ a little bit from one product family to another, there is still a similar strategy to solve them. Capturing the design rationale for such issues can be standardized by providing IBIS templates. In the IBIS template, the potential issues and their corresponding options and arguments are listed, and as the design proceeds, the designer fills in or updates the template. Figure 5.13 shows an example of the parts that could be used to form the IBIS template. For example, as shown in figure 5.13, in case of low strength in a milling product, the first options that a designer should consider are the size of the screw and the amount of material between the insert seats.

Capturing design rationale for different stakeholders

Based on the findings from interviews, meetings and workshops, four types of information were identified to be captured for the stakeholders mentioned in table 5.1 (the first and second types are general and can be useful for all the stakeholders, while the third and fourth are more specific for product maintenance and special design), as follows:

1) Information explaining the product family, its application area and the possible configuration of parts included in the product. In addition, it is necessary to explain the core values of the family (why should this product family be chosen among the others?). Such information, in addition to providing an overview about the product, supports the engineers in providing the best solution for the customers according to their needs, not according to what product the customer thinks is best for them.

2) The major issues that have been solved during the development process. However, these issues should be those that will most probably arise again in a similar design project (this was discussed in figure 5.13).

3) A general description about each module in the CAD model, as well as a description about the module's geometry including the user parameters, what each parameter does, and what the acceptable range for the parameter is and why. Table 5.2 shows an example of such information that is captured for the Chip space in the milling product. P1, P2, and P3 are the Chip space’s parameters discussed in figure 5.13. Please consider that this is a simplified example.
4) Documenting the design decisions according to the QOC-based method discussed in chapter 4. MindManager was again selected as an application for capturing the design rationale since it simply allows use of templates (see figure 5.14; due to the company’s policy, the information in figure 5.14 is fictive). Each design alternative is identified by a number of parameters such as diameter and insert size and a picture for a better illustration of reasoning. The three criteria sources, marketing, engineering design, and manufacturing, are presented in front of each design alternative. The color of each criterion shows if the design alternative meets the criterion or not (gray: neutral, red: negative, and green: positive). The argument written in front of the criterion is the result of the evaluation of the design alternative against the criterion. Four types of decisions are pre-defined for the sake of simplicity and standardization. The decisions are:

- **Design alternative eliminated**: this is when the design alternative violates one or several criteria
- **Design alternative eliminated, but can be conditionally accepted**: this is when the design alternative is eliminated but can be accepted under specific circumstances (this is very helpful for special engineers who develop products with specific requirements).
- **Design alternative accepted**: this is when the design alternative meets all or some of the major criteria.
- **More investigation is required**: this is when the design alternative is under investigation and for example, the engineers wait for results from a prototype test.

Capturing design rationale according to figure 5.14 was presented for the engineers in the company. They liked the idea; however, adding a new application (MindManager) to the design tools was a concern for the engineers. The model presented in figure 5.14 was modified by replacing MindManager with Excel (because it is used currently in the company and the designers are familiar with it). A template in Excel was created with rows for the design alternatives including number and picture; the three criteria sources; and the decision including action, date, and decision maker in columns. The decisions can be selected from a drop-down menu. Figure 5.15 shows the template filled in by the four design alternatives.
Figure 5.14 Capturing design rationale based on the QOC method.

The written arguments in each cell are very valuable for product maintenance and special design. They give a quick overview of the design alternatives and why they were selected or eliminated. Hyperlinks can be used if more knowledge is required. For example, a hyperlink is created in the cell “risk of low strength in the product” that opens the report that analyzes the results of the simulations for that design alternative.

More information can be found in paper 7.
Managing Design Rationale in the Development of Product Families and Related Design Automation Systems

Sharing design rationale for stakeholders

The four types of information presented above is to be shared with the stakeholders (product maintenance and special design). They need to know why the products are developed the way they are, but they do not need all the information. The information provided to them should also be of the same version as when the product specification (CAD models and other documents) where generated through the product model.

Two types of sharing were identified in this study:

Passive share is to share the information with the aftermarket stakeholders after production release. This was done by providing a package of all four types of information in the form of PDFs and e-pubs, that is, e-books. For more information, please see paper 7.

Active share is to share the design rationale through the CAD environment in run time. The aim is to support the designers during their design practice. Providing all four types of information during run time would be too much for the engineers. Regarding the special engineers, they were very interested in the fourth type of the information, therefore, it was decided to share only the fourth type of the information in the CAD software. To achieve that, a plugin to the design automation program was developed. The development of the plugin is out of the scope of this thesis (for more information, please refer to paper 7). The plugin enables the engineers to write comments for a code block in the web page format (xhtml-fragments that support rich text and pictures) directly into the design automation program. Therefore, it is possible to add the important content into the programming code in a format that fits the content itself: text and pictures (movies would be possible as well but were not relevant). When hovering the mouse over or right clicking on a node, a pop-up window shows the comment in a web page format. In addition, the plugin allows the engineers to access that information through the CAD software used in the company during run time. For example, as shown in figure 5.16, if a special designer wants to change the number of inserts in the product, the information that was captured previously (figure 5.15) is presented to him/her through a pop-up window in the CAD software.

Figure 5.15. Capturing design decisions and their rationale in Excel.
5.3.3 Analysis of the prototype system

The design rationale for the whole product family is captured into the product family model. The executable product family model can provide different views of this knowledge for different stakeholders. When the product family is released to the market, the sharing of the design rationale can be done in two ways. One is to share the design rationale during the run time process (active share), as presented in figure 5.16. In this way, only the design rationale for a specific design instance is shared. The other is to share the design rationale for the whole product family (passive share) in form of PDFs and e-pubs (discussed in paper 7). This type of sharing includes all four types of information discussed in section 5.3.1.

The worksheet presented in figure 5.15 provides the answers to the five (out of six) questions discussed in section 3.5 that are required for traceability:

- **What** product knowledge is created or represented?
  
  *Answer:* The design alternative, evaluation of the design alternative against the criteria, an argument for each criterion, and the decision that is made based on the evaluation are the represented knowledge.

- **Who** are the actors playing roles in creating or using the knowledge?
Answer: This question can be answered from two perspectives. One is the decision maker, who is responsible for creating the document. The other one is the person who has tested a prototype or has run a simulation for that design alternative. The latter usually documents his or her results in the form of test reports or technical memos. Hyperlinks to the test reports and meta knowledge can be provided to specify the owner of that specific knowledge.

The users of the knowledge are the stakeholders discussed before.

- **When** was the knowledge created or modified?
  
  *Answer:* Like the *who* question, it can be either the date that the decision was made, or the date that the design alternative was evaluated.

- **Why** was certain knowledge created or modified?
  
  *Answer:* The color of the cells and the arguments written in each cell provide explanations about why a specific decision was made for each design alternative.

- **How** is the knowledge being created or modified?
  
  *Answer:* This question can be answered by looking at the created knowledge that is behind this worksheet—the knowledge that is accessible through the hyperlinks.

In addition, the standardization of the decisions’ statuses and weighting the criteria make it easy to understand the decisions and grasp the logic behind them.

The parameters of the design alternatives need to be considered here. The geometry of an artifact is usually defined by several parameters in the CAD model. In the example shown in figure 5.15, diameter, insert size and number of teeth are the most important parameters and play significant roles in the product’s functionality. The suggestion is to define a design alternative by its most important and critical parameters. This makes it easier to further explore the design space based on the provided data. For example, based on the different values for the design parameters, charts can be created to investigate how the number of teeth is changed by changing the diameter. In addition, it makes it possible to filter or search for a specific parameter, for example, to search for all the design alternatives where diameter=25 mm. Searching and filtering, however, are not limited only to the design parameters. It is possible to search based on date, decision maker or a particular decision status.

### 5.4 SUMMARY OF THIS CHAPTER

Wiki was the application used in the first prototype system. The design rationale for the product was documented in several pages (articles in figure 5.1). Wiki was also used in the prototype system developed in the second case study. It was used to document the design decisions and their rationales including the design date, design team member, intentions and goals, assumptions, alternatives, and evaluations (these topics were inspired by the IBIS approach). In addition, Microsoft Word, Microsoft Excel, and SolidWorks were used to allow the users to capture and share design statements directly within the design software. The design rationale contains a number of statements and the decision, which were documented in the wiki page. The
URL address for the wiki page was attached to the design rationale. The content of the wiki was presented in the lower window in the prototype system.

A mind mapping software and Microsoft Excel were used for capturing the design rationale in the third study. Templates were created to support the designers in capturing the design rationale. In addition, a DSL-based application was developed to integrate the sharing of the design rationale into the design environment. The application enabled sharing the design rationale in the form of PDFs and e-books (passive share) or in form of comments and pictures in the CAD software in run time (active share).

Table 5.3 shows the comparison between the three prototype systems.

<table>
<thead>
<tr>
<th></th>
<th>Prototype system 1</th>
<th>Prototype system 2</th>
<th>Prototype system 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Access to the information</strong></td>
<td>Through the wiki website</td>
<td>Through the wiki website, Microsoft Excel, Microsoft</td>
<td>Through the DSL-based application in the design</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Word and SolidWorks</td>
<td>environment</td>
</tr>
<tr>
<td><strong>Implementation of the information models</strong></td>
<td>The information model was completely implemented</td>
<td>The information model was modified</td>
<td>The information model was completely implemented</td>
</tr>
<tr>
<td><strong>Users</strong></td>
<td>Designers and product maintenance engineer</td>
<td>Product designers, tooling designers and FEM engineers</td>
<td>Designers, special designer and product maintenance engineers</td>
</tr>
</tbody>
</table>

Table 5.3. The comparison between the three prototype systems.
CHAPTER INTRODUCTION

Qualitative evaluations were carried out on the results from chapters 4 and 5. The evaluations assisted in ascertaining the degree of achievement in regard to the objective and results of the research. The evaluations, in addition, enabled reflection and aided in the identification of further work.

The evaluations were conducted in the two case companies during meetings and workshops. The aim was to determine the merits and applicability of the methods and prototype systems. Qualitative questionnaires with open-ended questions were given to determine the quality and impact of the systems and their usefulness in the design practice. A number of questions, general enough to be answered by the practitioners in the companies, were provided. The participants who answered the questions had different roles with years of experience at the companies.

6.1 EVALUATION OF CASE STUDY I

A questionnaire was conducted in case company A that focused on the product family description (PFD) and the prototype system developed in wiki. The manager of the design automation department, a project leader, a designer, and a system developer (responsible for developing the design program) participated in the answering the questionnaire. They had all been involved in developing and implementing the system.

Table 6.1 shows a summary of the questions and answers. In general, the answers show that the participants were optimistic about the PFD and that it could be used to improve traceability and knowledge reuse. The project leader and the design automation manager considered the PFD a valuable tool for providing input to design programming, while the system developer believed it should be mandatory to have a PFD as the basis for design programming. With regard to the wiki used for documenting the product knowledge, there were some concerns about its efficiency in recording, categorizing and searching the knowledge. The design automation manager and the project leader both stated that more efficient documentation would result in cost savings for the company.

For further investigations, the participants would like to see more research on managing the PFD in regard to documenting and storing the knowledge. There was also a suggestion for evaluating other software alternatives to support the selection of the most suitable solution according to the company’s requirements.
Managing Design Rationale in the Development of Product Families and Related Design Automation Systems

Table 6.1. Evaluation of case study 1.

<table>
<thead>
<tr>
<th>Query</th>
<th>Design Automation Manager</th>
<th>Project Leader of Documentation Project</th>
<th>System Developer</th>
<th>Engineering Designer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. What is your opinion about PFD?</td>
<td>PFD is great. That’s a really good definition of our documentation at the company.</td>
<td>Great! I like the concept and will work for a PFD solution at the company.</td>
<td>The PFD is essential for traceability, knowledge reuse and a streamlined parametric and rule-based process</td>
<td>The current documentation at the company describes our product families. PFD is perhaps a better description for that in the future. Also, if we can implement the rationale part of this in an easy way it could be great.</td>
</tr>
<tr>
<td>2. What is your opinion regarding PFD as an input for design programming?</td>
<td>PFD is excellent. If it’s also divided in DMD, it’s easy to reuse and gets the needed knowledge for a family.</td>
<td>I think it will be great.</td>
<td>It should be mandatory to have a PFD as a basis for the design program.</td>
<td>If the PFD is created during PDP in close cooperation with design automation it generates good input for design programming.</td>
</tr>
<tr>
<td>3. What do you think about making structured documentation based on categories?</td>
<td>It can be a way. It’s like a template (for me).</td>
<td>If it would be possible to have it more in forms then it would be better. I mean that the properties and categories should have some kind of automatic handling.</td>
<td>Properties is one way of making the information structured. A structured information model is essential to leverage reuse of knowledge. By having a structured information model, it is possible to classify and search the information in a relevant way.</td>
<td>You should always strive to make the documentation in a structured way. It could be difficult to strictly document based on properties and categories. While documenting a product family, I think you have to make sure that there is a good overview of what is included in that particular family.</td>
</tr>
<tr>
<td>4. How do you think properties and categories can provide access to the stored knowledge?</td>
<td>It makes the documentation searchable.</td>
<td>Implementing in the right way would be helpful for information finding. But see question 3.</td>
<td>See answer for question 3.</td>
<td>When designing a new product, you can look for what is already made in a certain area. Can you reuse it?</td>
</tr>
<tr>
<td>5. What is your opinion about making documentation in the pre-defined templates?</td>
<td>I like that.</td>
<td>Great, I like it a lot and we will use templates in the future. In which way depends on the system solution.</td>
<td>This is part of an information model. The template represents the class of the information, and the document based on a template is an instance of that class. See template as a contract or interface for consumers of the information (and by consumers, I mean humans or other systems).</td>
<td>With pre-defined templates, you are helped in making documentation; it’s easy to see what is expected from you. For new designs it should be great, and also the format for the documentation will be more streamlined.</td>
</tr>
<tr>
<td>6. How can the results of the project be used at the company?</td>
<td>We will implement PFD and DMD. Probably not the other, at least not now. We have to see what our RBD project comes up with.</td>
<td>PFD will definitely be used. SMW is under consideration but mostly without the semantic part.</td>
<td>The important result of the work is to emphasize on the need to classify information. I haven’t seen enough of SMW to have a well-founded opinion about it, but as I see the future of PFD’s and design rule documentation I would say that SMW does not suffice. In the long term, the PFD recording application should support the creation and versioning of runnable design rules and that is not possible with any known system today. But the technology is available for creating such a system and I think that should be the long-term goal.</td>
<td>It can be a source of information and insight during future work within rule based design at the company.</td>
</tr>
<tr>
<td>7. What are the drawbacks of the project results?</td>
<td>I don’t see any drawbacks. Although I would like to have more focus on DMD as a part of the whole Description parts. For me it feels that we can document Design Modules separately and by inheriting various PFDs. That’s a way of reusing knowledge.</td>
<td>Maybe should have been considered having a look at SharePoint.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. What is needed for further investigation?</td>
<td>We will investigate a way (system?) to document and store documentation about PFD.</td>
<td>How can the designer handle the PFD in the most efficient way?</td>
<td>See answer for question 6.</td>
<td>To look into more software alternatives and decide what is most suitable for our requirements.</td>
</tr>
</tbody>
</table>

6.2 EVALUATION OF CASE STUDY 2

The evaluation session in company B was started by a presentation of the system that was followed by a discussion, and in the end, the questionnaires were distributed to be answered. The product development manager, the chief engineer for racks, and the tooling designer participated in the evaluation and were asked to answer the questions. However, the participants preferred to answer the questions in a single document unanimously.

Table 6.2 shows the questions and a summary of the answers of the three participants. Overall, the participants affirmed the possibility of employing such a system in the design implementations in the company. They stated the great advantage of linking the related information across the software, especially between CAD models and Excel. It was acknowledged that such functionality would definitely facilitate tracing the effected knowledge when updates are required across the product documentation in the company.
Although the participants would like to test the prototype system in the organization across the broad in a larger scale, they are optimistic that the benefits would outweigh the efforts. However, the maintenance of an additional system and the need for learning and understanding the system by the users were the concerns stressed by the participants.

The suggestions for further improvements were to link the Excel file to the 2D-sketches in PDF format and to provide a view of the CAD model in Excel to be used by the practitioners who do not need to have access to the CAD software.

Table 6.2 Evaluation of case study 2.

<table>
<thead>
<tr>
<th>Query</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. What is your opinion about the system?</td>
<td>It is a good way to link the CAD model to other types of information and keep the documentation up to date.</td>
</tr>
<tr>
<td>2. Can this system be used at the company?</td>
<td>Yes.</td>
</tr>
<tr>
<td>3. Who should be responsible for managing, editing, and maintaining the knowledge and system at the company?</td>
<td>It should be IT or R&amp;D departments. More investigation is required.</td>
</tr>
<tr>
<td>4. What are the drawbacks of the system?</td>
<td>Maintenance of an additional system.</td>
</tr>
<tr>
<td></td>
<td>Understanding and learning the system.</td>
</tr>
<tr>
<td></td>
<td>Whether the system will slow the performance of the computer.</td>
</tr>
<tr>
<td>5. What can be improved?</td>
<td>Additional tools enabling a 3D view of the CAD models, for instance, in Excel, without need for using the CAD software.</td>
</tr>
<tr>
<td></td>
<td>View of the connections in the 2D-PDF sketches.</td>
</tr>
<tr>
<td>6. Will the benefits outweigh the efforts and costs of resources required?</td>
<td>Probably.</td>
</tr>
<tr>
<td>7. What is needed for further investigation?</td>
<td>A system capable of being used with other systems in the company.</td>
</tr>
<tr>
<td></td>
<td>Cost of the system and return of investment.</td>
</tr>
<tr>
<td>8. What would you like to see as next step?</td>
<td>A prototype system that can be tested.</td>
</tr>
</tbody>
</table>

6.3 EVALUATION OF CASE STUDY 3

The results of the research presented in sections 4.4 and 5.3 were examined by the engineers in the company through three workshops. The first workshop, which was in the middle of the research project, was organized for the engineering group (a group consisting of five engineers from different departments who were involved in the research project). The second workshop was organized for all the special designers across the globe. The results of the research were presented in the first and second workshops and the engineers’ feedback was used as input to further develop the methods and tools that they were presented later in the third workshop. The third workshop, which was at the end of the research project, was organized for the engineering group.

The workshops included a presentation of the methods and tools and followed up with questionnaires to get feedback from the engineers. Table 6.3 shows the evaluation from the second workshop, and table 6.4 shows the evaluation from the third workshop. The answers from all the engineers are merged into one answer that covers the important points that were mentioned by the engineers.
During the second workshop, a document including all four types of design rationale was presented. The possibility of accessing some part of the rationale through the CAD software was also presented. Then, the engineers were asked to answer a number of questions regarding the design rationale and the way of sharing it. All of them stated that this is a good way of representing design rationale and that this type of rationale can help them get an overview of the design space. They also mentioned that they could save a lot of time if the right information was provided for them (see table 6.3).

Although the engineers believe that this type of information will help them when performing their tasks, it is still not possible at this early stage to evaluate the results and whether the benefits outweigh the time and resources required for capturing the rationale. A real evaluation would be possible if the special designers use this knowledge when a special order of the selected product family is requested.

Table 6.3. Evaluation of case study 3 by the special designers.

<table>
<thead>
<tr>
<th>Query</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Do you think that these four types of information can be a</td>
<td>Yes, it is a good starting point.</td>
</tr>
<tr>
<td>starting point for representing the design rationale for the special</td>
<td></td>
</tr>
<tr>
<td>designers?</td>
<td></td>
</tr>
<tr>
<td>2. Do you think that classifying the information in this way can</td>
<td>Yes. Not being able to find what we search for is one of our most</td>
</tr>
<tr>
<td>save time for the special designers when they search for</td>
<td>time-consuming activities.</td>
</tr>
<tr>
<td>information through such a document?</td>
<td></td>
</tr>
<tr>
<td>3. What do you think about the product constraint example? Is</td>
<td>It is great. It can give us an immediate idea of what is possible and</td>
</tr>
<tr>
<td>such detail of rationale useful (the worksheet in Figure 5.15)?</td>
<td>not possible in a product.</td>
</tr>
<tr>
<td>4. What do you think about the chip space example (information</td>
<td>Yes, this is what we need.</td>
</tr>
<tr>
<td>in table 3.2)?</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.4. Evaluation of case study 3 by the engineering group.

<table>
<thead>
<tr>
<th>Query</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. How will the developed methods affect traceability between</td>
<td>Traceability will increase by implementing the methods. Uncertain</td>
</tr>
<tr>
<td>product requirements, programming code and production</td>
<td>how it should be implemented.</td>
</tr>
<tr>
<td>requirements?</td>
<td></td>
</tr>
<tr>
<td>2. Will the method contribute to a better overview of the</td>
<td>Yes, with a good implementation.</td>
</tr>
<tr>
<td>information?</td>
<td></td>
</tr>
<tr>
<td>3. Will it be possible to keep the relationships updated over the</td>
<td>Version handling and a common model are required.</td>
</tr>
<tr>
<td>long term (several years)?</td>
<td></td>
</tr>
<tr>
<td>4. Will it be easier to understand a product family?</td>
<td>Yes.</td>
</tr>
<tr>
<td>5. Will the system cut the time it takes to understand the</td>
<td>Plausible.</td>
</tr>
<tr>
<td>relationships between design practice and programming code?</td>
<td></td>
</tr>
<tr>
<td>6. The following producers and consumers of information are</td>
<td>Designer needs development support</td>
</tr>
<tr>
<td>identified: Design engineer, Design programmer, Special</td>
<td>Programmers need PFD (Product Family Description)</td>
</tr>
<tr>
<td>design engineer, Production preparation engineer. What kind of</td>
<td>Production preparation engineer needs PFD</td>
</tr>
<tr>
<td>information do they need?</td>
<td>Special engineer needs design rationale</td>
</tr>
<tr>
<td>7. Can their need for information be better fulfilled if the</td>
<td>Yes, for special designers and design engineers. Plausible to others.</td>
</tr>
<tr>
<td>proposed method is introduced?</td>
<td></td>
</tr>
<tr>
<td>8. How will the time it takes for documentation be affected?</td>
<td>Tends to increase.</td>
</tr>
<tr>
<td>9. Will the system contribute to any of the following? Shortened</td>
<td>Developing time: No</td>
</tr>
<tr>
<td>development time, more efficient use of resources, increased</td>
<td>Tends to increase.</td>
</tr>
<tr>
<td>collaboration, increased quality of documentation.</td>
<td>More efficient use of resources: Yes, for special and maintenance</td>
</tr>
<tr>
<td></td>
<td>engineers</td>
</tr>
<tr>
<td></td>
<td>Increased collaboration: Yes</td>
</tr>
<tr>
<td></td>
<td>Increased quality of documentation: Yes, if it is implemented correctly.</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>10.</td>
<td>Will the system in any way contribute to increased customer value? If so, how?</td>
</tr>
<tr>
<td>11.</td>
<td>Who inputs and who reviews the design rationale?</td>
</tr>
</tbody>
</table>
CHAPTER INTRODUCTION

In this chapter, a summary of and reflection on the research are provided first. Next, the work is evaluated by resuming the research questions. The validity of the research is discussed through a number of factors. Finally, a discussion of the research procedure is provided.

7.1 SUMMARY OF RESULTS

Developing customized products is a competitive advantage for many manufacturing companies. The work of generating new product variants according to new customer specifications can be carried out more efficiently by applying design automation systems to automate the time-consuming and repetitive design tasks. This is a strategy for companies to reduce time and cost and to provide a higher degree of customer adaptation. The maintenance of design automation systems is essential to retain their usefulness over time and adapt them according to changes.

This section provides a summary of the results of the three case studies and a reflection on the research.

7.1.1 Including design rationale in product information models

The modeling and management of product knowledge was investigated in paper 1. To efficiently document the product knowledge and aid traceability, the information models were presented (figure 4.1 and figure 5.3). The information models mainly explain that the product knowledge documentation required for a design automation system should include both the design definition and the design rationale. It was seen in paper 1 that traceability has a significant impact on system use and maintenance by linking the design definition to the design rationale and the supporting documents.

Further, the focus of the research was directed toward managing the design rationale, including capturing, structuring and sharing through case studies 2 and 3.
7.1.2 Capturing, structuring and sharing design rationale across product design and tooling design

In case study 2, the objective was to enable capturing the design rationale during the design implementations in a suitable format when a decision is made. In case study 2, an information model (figure 4.3) was developed. The information model enables representing the design rationales including the design decisions. Using the design software that are commonly used in the design process and that the designers are already familiar with was suggested for capturing and sharing. The benefit of this integration is that it allows the selection of software according to the needs and goals of the companies. This allows an easier integration of the design rationale system with its external environment, other systems, and the IT-infrastructures in the companies.

A successful design rationale system should have the ability to monitor, browse, search, edit, and filter the information according to need. This enables the system to display the required detail of the information relevant to the problem at hand; moreover, it supports the management of the information. The common user interface embedded in each type of software enables the designers to browse and navigate through the design rationales across different phases such as product design, FEA, production, etc. This allows the engineers to assimilate all the relevant cues and examine all the potential effects of their decisions.

Having an instruction for capturing design rationale is required for recording the right amount of information with the right quality and for less intrusion into other design activities. Therefore, a checklist was provided for capturing the design rationale at two levels: the component level and the assembly level.

7.1.3 Capturing, structuring, and sharing design rationale for a product family space

To complete the method for capturing, structuring and sharing design rationale, the focus of case study 3 was answering the following questions:

- Who are the stakeholders of the design rationale?
- What information and knowledge should be captured?
- When should the design rationale be captured?
- Who should capture the design rationale?
- How should the design rationale be shared with the stakeholders?

It is necessary to consider the “use” of the design rationale to make the capture worthwhile. This was the focus in case study 3, where first, an exploratory study was performed to identify the stakeholders of the design rationale in the development of product families and the rationale that they need. IBIS an argumentation-based approach, was used to capture the design rationale. IBIS was used mainly for documenting how the major issues in design were solved. Such types of information are useful for all stakeholders.

To capture more specific design rationale for the special design and product maintenance engineers, the development of the design space and the evaluation of the design alternatives were targeted.
Marketing, manufacturing and engineering design were identified as the driving criteria source in the product family development process that led to the final design. Based on the identified criteria, a QOC-based approach for capturing, structuring, and sharing the design rationale for the product family space was developed. The use of templates seems to be a good strategy for shortening the time for capturing design rationale and structuring and standardizing the documentation.

Two types of sharing were studied: sharing the design rationale in run time in a CAD environment for a specific design instance only, and sharing the design rationale for the whole product family in the form of PDFs and e-books, as discussed in paper 7.

### 7.1.4 Reflection on research

The importance of design rationale for design reuse and design maintenance was studied in case study 1. Methods are required to support capturing, structuring and sharing design rationale. The methods should enable the easy management of design rationale integrated into the engineering tools to foster their use. This can be achieved by integrating the capture and share processes in the design tools. This was addressed in case study 2; however, one limitation in the introduced method is the lack of a shared base to allow the engineers to record the design rationale in a common form that is understandable for all the other users, not just some texts and comments that can be understood only by the persons who have recorded them.

In this research, sharing design rationale was supported by developing extensible applications integrated into the software that the designers are using to make the information instantly accessible. However, a bottleneck in such user interfaces is keeping their efficiency and simplicity when the captured information increases.

Regarding the argumentation-based approaches used in case study 3, both IBIS and QOC have their advantages and limitations. An advantage of IBIS is that it covers all the elements of the design rationale, such as issue, option, argument, and decision. However, such functionality might sometimes lead to information overload. The QOC, however, is a more condensed version of IBIS that targets capturing design rationale for a design space. However, the rationale captured based on the QOC approach is mostly useful for understanding the decisions that deal with evaluating the design alternatives. A challenge in the QOC approach is the combination of the design parameters to form a design alternative. Due to the high number of design parameters, the number of potential design alternatives explodes. Therefore, it is necessary to identify those design parameters that have strong roles in the design.

### 7.2 EVALUATION OF THE RESEARCH

The evaluation of the thesis is done first, by returning to the research questions. Then, discussions regarding the validity of the research based on the factors discussed in section 2.5 are provided.

#### 7.2.1 Resuming the research questions

The research questions for this study to support the overall purpose of the research were as follows:
RQ1. How could the design rationale be captured during the product development process?

RQ2. How could the design rationale be structured during the product development process?

RQ3. How could the design rationale be shared during and after the product development process?

A summary of the answer to each question follows:

**RQ1. How could the design rationale be captured during the product development process?**

This question can be answered through three steps as below:

**What should be captured?**

Four types of information to be captured for the stakeholders of the design rationale across the product life cycle were identified:

- The first one is to explain the product family, its application area and the possible configuration of parts included in the product. In addition, it is necessary to explain the core values of the family (why this product family should be chosen among the others). This information is suitable for all stakeholders but will mostly be used by those stakeholders who are interested in the design rationale after releasing the product to market, for example, product maintenance engineers, special designers, or even new designers. Such information, in addition to providing an overview about the product, supports the engineers in providing the best solution for the customers according to their needs, not according to what product the customer thinks is best for them.

- The second one is to document those major issues that regularly arise during the development and the strategies for solving them. The suggestion is to use IBIS-based templates for capturing this type of rationale. This information is basically suitable for all stakeholders across the product’s lifecycle.

- The third one is to explain the important parameters in the CAD models, what each parameter does, what the valid min/max values for each parameter are, and motivations for the min/max values. This information is basically suitable for all stakeholders across the product’s lifecycle but mostly for product maintenance engineers and special designers.

- The fourth one is to capture the rationale regarding the evaluation of the design alternatives based on QOC and the identified criteria. The QOC model provides a quick understanding about the design space, which is very interesting for product maintenance engineers and special designers.

**How to capture?**

In order to reduce the intrusion to design process because of capturing design rationale, the suggestion is to embed capturing the design rationale as closely in the design activities as possible. This can be achieved by enabling the users to capture the design rationale in the design software that they are already using to do their work.
Thus, the user does not need to open an additional tool for the sole purpose of capturing the rationale.

Since accomplishing the design activities entails using different independent software, integrating the design software will allow the users to capture the design rationale in a range of formats that the available design software in the organization supports. The suggestion for creating such integration is to implement extensible applications into the design software to enable capturing the rationale in the appropriate software. The application should have the ability to target the information in each type of software and connect the related information together in the different software.

When to capture?

The author's experience shows that capturing design rationale in the end of a development project is not an efficient approach. Therefore, the suggestion is to capture the design rationale concurrently as the design proceeds. It is also necessary to review the captured design rationale. Milestones can be provided for the design team (or an expert person) to review the decisions. An example for a milestone could be when the engineers analyze a tested prototype.

RQ2. How could the design rationale be structured during the product development process?

Templates can be created to support the structuring of the design rationale. This was done in case study 1 by providing templates in wiki. Similarly, templates for decisions were created in case study 2, including intention and goals, assumptions, alternatives, and evaluations. In case study 3, Issue-based templates and QOC-based templates were created to support the structuring of the design rationale.

In addition, structure is achieved by the proposed information models as presented in the UML diagrams in case studies 1, 2 and 3. The information model in case study 1 enables inclusion of the design rationale in the product knowledge model. In case study 2, the decision class makes it possible to group and map the related statements across different disciplines and knowledge sources. This facilitates traceability to pursue the affected information when a part of the knowledge needs to be updated. The information model in case study 3 enables the classification of the decisions based on the criteria sources (marketing, production, and engineering design). Therefore, it is possible to select a criterion and filter all the decisions for that criterion.

Categorizing the information in (virtual) folders or tagging the related information are some techniques used to support structuring.

RQ3. How could the design rationale be shared during and after the product development process?

During the development process, the information should be shared instantly when it is captured, preferably through the design software. Providing instant access would be more likely to encourage the designers to capture the rationale because they know the information can benefit them or their colleagues in the moment, not some years later during future design projects. A suggestion is to provide a user interface to facilitate
intuitive human computer interaction. This can be supported by developing extensible applications integrated into the design software that the designers use, in order to make the information accessible whenever it is required. Access to design rationale can be strengthened by enabling the user to quickly list, view, and browse the design rationales across the documents.

For stakeholders after the production release, two types of sharing are provided: active share and passive share. Active share is sharing the rationale in run time with the stakeholders according to their current design activity. For example, when a designer wants to change a parameter or modify a design variant in the CAD environment, the design rationale for that parameter or that design variant is accessible through a pop-up window in the CAD software in the form of comments, tables, and pictures. Passive share is a package of information about the product family that is tailored for a specific stakeholder (in the form of PDFs or e-books) and is available when the product family is released to the market.

Further, in this thesis, the importance of providing a database or a central server to support the sharing of the design rationale among the design members was emphasized. The search techniques, in addition, can facilitate the users in retrieving the information.

7.2.2 Validation of the research

Five factors were described in section 2.5 for evaluating the validity of the results. The research was evaluated through the following review of the factors:

Internal logic

To prove the validity of the research, it is necessary to show that the result is based on accepted theories and that the work is stringent from the problem definition to the result. The theoretical base for the research was formed by reviewing literature seeking to summarize and evaluate the research in design rationale management and studying the available tools and methods. The scope and purpose of the thesis were formed, and the thesis was conducted by problem definition and recognition of needs for improvement, an approach for carrying out the research with theoretical and application-oriented aims, and a method for evaluating the results. The use of well-known argumentation-based approaches, such as IBIS and QOC, and well-known design rationale tools, such as Dred, that were developed by the research community for evaluating the results, as well as the use of the DRM for conducting the research, show the internal logic of this research.

Truth

The two case companies have long traditions of applying automation systems in different stages of their development processes. The need to manage the design rationale to efficiently utilize and maintain the design automation systems was demanded in both companies in order to be able to deliver their customized solutions faster.

The results achieved in the thesis were tested through case studies in the companies by selecting test products and building prototype systems. The evaluations of the
prototype systems were based on the opinions of the practitioners in the companies, regardless of the researcher’s point of view or other biases.

**Acceptance**

The research presented in this study is based on a combination of industrial needs and an academic knowledge gap. Acceptance in a peer-reviewed journal and conferences that address solutions for the identified challenges accredit the research results from the academic point of view. In order to verify the results from an industrial perspective, the developed solutions and prototype systems were tested and evaluated in the case companies during evaluation sessions and workshops. The validation was primarily based upon the feedback from experienced engineers. The research results were presented to the engineers and discussions between the engineers and researchers were encouraged. It can be concluded from chapter 6 that the usefulness and applicability of the results of this research have been affirmed by the practitioners in the case companies.

**Applicability**

The applicability of the results was tested through three case studies. Although the investigations in the case studies show the benefits of the proposed solutions and their potential in supporting the utilization and maintenance of the design automation systems, at this early stage, it is not possible to measure the improvement of the situations. As an example, the applicability of the results of case study 3 will be accredited only when the special designers receive an order and they refer to the design rationale provided for them. Since the tested product family was recently released to the market, it might be a few years before a customer requests a special product.

**Novelty value**

Design rationale has been a topic of research for many years. Many tools and systems have been developed to support the different aspects of design rationale, but just a few of them might be used in practice. The literature review of design rationale systems provided in chapter 3, presents some similar contributions in this context. For example, the use of IBIS and QOC has been investigated by many researchers previously. What is new in this thesis is analyzing these methods in the development process by using different applications such as Wiki, DRed, MindManager, and worksheets. The differences are investigated, and solutions are provided that explain which method is suitable in which context. In addition, according to the author’s knowledge, identifying the stakeholders and their needs during the product lifecycle, capturing and sharing design rationale according to those needs, and studying the capture, structure, and share process as a whole, specifically in the context of design automation has not been addressed by the research community.

General frameworks and models for traceability had been previously developed, for example the model introduced by Ouertani et al. [26] which includes the *what*, *why*, *who*, *how*, and *when* questions. In this research, these questions were explored in more detail and the challenges were investigated.

The integration of design rationale capture and share through the design practice had been studied before. For instance, providing annotations to record an argument in CAD
software or hyperlinks to link to other knowledge sources. What is new in this thesis is enabling the users to simultaneously work in an integrated environment of design applications and to embed the capture, structure, and share processes together. Such an environment will facilitate collaboration among the design teams and allow the management of the design rationale across the domains and applications.

7.2.3 Discussion concerning the research procedure

To sum up the research, support for the utilization and maintenance of product families and the related design automation systems have been developed and evaluated. The research was carried out based on the approach discussed in section 2.4. Information models and computer-based models were developed that aimed to improve the design practice.

The DRM method was used for conducting the research. The DRM consists of four stages that assist in making plans to implement and progress the research, study the current situation and need for further improvement, develop the support, and evaluate it. In this thesis, methods and tools were developed and evaluated by the engineers in the companies. It can be concluded that the research has been in line with the fifth type of the DRM method discussed in section 2.2.1.

A review of the research questions and the gained results indicates that they are general enough to be applied to the product family development processes in other companies. However, to ensure that, further investigations are essential to expand the research findings across other product platforms.

The practice of scientific research requires rigor in the researcher’s work. The thesis provides a thorough description of the steps taken during the research. The clarity in the research makes it possible to show that the findings are accurate, fair, and free from bias.
CHAPTER 8

CONCLUSIONS AND FUTURE WORK

CHAPTER INTRODUCTION

In this chapter, the research work is concluded and the need for future research is addressed.

8.1 CONCLUSIONS

The capture, structure, and share of design rationale, especially in the context of mass customization and design variant, is an important topic that the research community has addressed for years. Chapter 3 indicates the importance of managing design rationale in a wide variety of industrial firms. Despite the efforts put into this topic, there is still a need for professional solutions that are easy to implement and use.

The modeling and management of product knowledge was investigated in case study 1. To efficiently document the product knowledge and aid its traceability, an information model was presented. The concept of PFD (product family description) was introduced that included both the design definition and design rationale to support design reuse and design maintenance. The PFD was implemented in company A through a wiki-based application. The usefulness of the information model and the provided application were confirmed by the company representatives in general which indicates the applicability of the provided solution in the development environment. The need for further investigations and supporting tools to efficiently feed the systems with the right amount and quality of knowledge was also stressed.

In case study 2, the objective was to enable the capturing and sharing of the design rationale during design implementations in a suitable format whenever a decision is made. Information models were developed to enable the representation of the design rationales, including the design decisions, and to support concurrent development between the different phases of the development process. To capture and share, the suggestion was to use the types of design software that are broadly used in the design process and that the designers are already familiar with. The benefit of this integration is to allow the selection of software according to the needs and goals of the companies. This allows an easier integration of the design rationale systems with their external environments, other systems, and IT-infrastructures in the companies. The prototype
Managing Design Rationale in the Development of Product Families and Related Design Automation Systems

System of integrating SolidWorks, MS-Excel, MS-Word, and wiki was developed to examine applicability of the proposed model for managing design rationale. The aim was to choose some of the common and popular design software. The system was tested through a design automation system where a focus was set on the need to share knowledge between FEA and product design. The system was also tested across product design and tooling design processes due to the significant need of information exchange and collaboration among involved design teams when developing custom engineering products. The findings have made it clear that the introduced system can facilitate the information exchange and the navigation of design rationale across the development process of customized products.

The focuses in case study 3 were mainly identifying the stakeholders (producers and consumers) of design rationale, capturing design rationale according to the consumers’ needs, and sharing design rationale during the development process and after production release. Marketing, manufacturing, and engineering design were identified as the source criteria that drive the product family development process. Therefore, it is very important to trace these criteria, not only during the development process, but also across the product lifecycle. This was addressed in case study 3.

Capturing and sharing design rationale are two fundamentally different functions that must be coherently aligned. Capturing design rationale without sharing it is useless. Sharing the design rationale with stakeholders facilitates its reuse and supports the designers in solving similar design problems. There is always a trade-off between allocating resources for capturing design rationale and how much the company gains from using design rationale. It is not efficient to capture the reasons behind every single design activity. So, answering the question “What design rationale should be captured?” totally depends on the consumer’s need. Some suggestions are to capture the decisions that directly address the design goals and requirements, to capture the decisions that limit the design space, to capture the strategies for solving the major issues that arise during similar design processes, and to capture a description about the product family, including its core values, application area, advantages over the other products, and its possible configurations.

The thesis was carried out as a part of two research projects, and the findings were implemented and evaluated in two case companies. Both companies develop and manufacture customized products; however, they differ in the types of products and development processes. Developing new design variants according to customer demands is a competitive factor for both of them. Therefore, the use of design rationale supports the engineers in both companies in understanding the design and responding to customer needs.

The results of the research were evaluated by the engineering groups in the companies. Although, a real evaluation of the results would occur when the designers use the information presented in this research, the feedback from the evaluation workshops in the case companies show the potential benefits of the presented solutions. The practitioners at the companies found the proposed tools and methods helpful and that they could considerably save time and cost during the development of new product variants. Some of the advantages are: identifying the stakeholders of the design rationale; capturing the design rationale according to the needs of the
consumers; embedding design rationale capture, structure, and share in the design implementations; and representing the design rationale in a proper format.

8.2 FUTURE WORK

The need for effective utilization and maintenance of design automation systems was studied in this thesis. However, issues still remain regarding the quality and version control of the captured design rationale and documentation. More research is required on the updating and version control of the captured design rationale as the development proceeds.

There is always a trade-off between allocating resources for capturing design rationale and how much the company gains from using it. To confirm the applicability of the developed methods and tools and their impact on the current situation, it is necessary to evaluate the results on a broader scale. More design rationale needs to be captured and shared across the products, processes, and systems to quantify the enhancement and identify the balance between the required effort and gained benefits. In addition, how the engineers and their work will be affected by implementing the solutions provided in this research requires more investigation.

The methods and tools introduced in this thesis support design maintenance and design reuse. However, the way the consumers of design rationale interpret the shared information and how successful they would be in reusing and maintaining the design has not been addressed. This could be an area for further research.

Currently, the prototype systems have been tested on local computers. Therefore, it is not possible to exchange the information across networks. Centralizing the system on a server and providing a database to facilitate collaboration and communication among a group of engineers would allow the engineers to assimilate the relevant cues and examine the potential downstream effects of their decisions even if the engineers are not co-located. This can be investigated in future research.
REFERENCES


47. Johansson, J., Combining Case Based Reasoning and Shape Matching Based on Clearance Analyzes to Support the Reuse of Components. 2012.


51. Stolt, R., CAD-model parsing for automated design and design evaluation. 2008, Jönköping University.


Managing Design Rationale in the Development of Product Families and Related Design Automation Systems

57. Bonev, M. Enabling Mass Customization in Engineer-To-Order Industries. in A multiple case study analysis on concepts, methods and tools. 2015. DTU Management Engineering.


65. Bermell-Garcia, P., A metamodel to annotate knowledge based engineering codes as enterprise knowledge resources. 2007.


86. Hooey, B.L., J.C. Da Silva, and D.C. Foyle, A design rationale capture tool to support design verification and re-use. 2012.