MASTER THESIS

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RaDEX: A Rationale-Based Ontology for Aerospace Design Explanation

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Abstract

The process of designing aircraft systems is becoming ever more complex and sophisticated, due to an increasing amount of requirements especially relating to technology and performance. Moreover, the knowledge on how to solve these complex design problems becomes less readily available, mainly due to the absence of systems to facilitate quick and easy access to information and knowledge that could significantly improve design work. This is against a backdrop of the rich knowledge that is created in the course of the design process but is unfortunately not always successfully transferred for the benefit of future projects to help explain why certain design choices were made or why some design solutions were selected.

Taking a design rationale capture perspective to solve this problem, the study reported in this thesis follows a design research approach to propose a Rationale-based Design Explanation (RaDEX) framework as an ideal representation schema by drawing from and integrating theories of explanation, design studies and design rationale research. The framework forms the basis of the RaDEX ontology that is proposed as a useful schema to record design rationale. Preliminary empirical evaluation of the ontology in a case study as a proof of concept to demonstrate its efficacy showed promising results with adequate scores of usefulness and ease of use from the perspective of design engineering practitioners.

The research provides a goal-oriented approach to design rationale research by addressing rationale capture requirements with respect to required content for effective and satisfactory design explanation, a direct consequent from real problems in design practice. Scientific contributions offered by the thesis include a design explanation model, derived by applying differing scientific accounts of explanation to the design domain, which identifies key points where explanations are required and the necessary content to answer design why-questions; a different notion of design rationale as the link between design solutions, requirements and selection criteria; and an ontology-based design rational capture method. A practical output of the research is a rationale-based ontology which can be adopted by design organizations as a schema to define knowledge-based design rationale capture systems.

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1 Introduction

We know more than we can tell.

Michael Polanyi (1967: 4)

This thesis examines the concept of design rationale as a useful way of documenting design knowledge that is created in the process of designing aerospace components. The aim is to capture enough relevant knowledge to enhance the explanation of design solutions. The study reported here proposes a Rationale-based Design Explanation (RaDEX) framework by drawing from and integrating theories of explanation; design, in particular aerospace design; and design rationale. The framework forms the basis of the RaDEX ontology that is proposed as a useful schema to record design rationale which is captured with the aim of helping to explain aerospace component designs. This introductory chapter provides the background and motivates the thesis topic; it sets out the problem statement, and outlines the key objectives of the research. It also specifies the research questions and presents an overview of the research methodology.

1.1 Organization Context

The research project has been carried out within the Knowledge Management unit (Tools and Methods Department) of Fokker Aerostructures B.V., an innovative aerostructures specialist company that is active in Europe and the USA. The company develops and produces advanced and lightweight components and systems for the aviation and aerospace industry along four main business lines: Business Jets, Large Commercial Aircraft, Landing Gears and Defense. Fokker delivers integrated aircraft structures and modules based on multiple advanced technologies and light-weight materials. Deep aerospace know-how, manufacturing effectiveness on a global scale and recognized innovative skills are the companies added value. Fokker performs Engineering, Manufacturing, after sales support and Program Management. Fokker Aerostructures is a strategic unit of Fokker Aerospace Group with 1750 employees.

1.2 Background

The process of designing aircraft systems is becoming ever more complex and sophisticated, due to an increasing amount of requirements especially relating to technology and performance (Moir & Seabridge, 2008, p 407). Moreover, the knowledge on how to solve these complex design problems becomes less readily available, mainly due to the absence of systems to facilitate quick and easy access to information and knowledge that could significantly improve design work. This is against a backdrop of the rich knowledge that is created in the course of the design process but is unfortunately not always successfully transferred for the benefit of future projects. Engineering design is a knowledge-intensive activity (Gruber, 1990). This means that throughout the product life cycle, designers need access to relevant engineering knowledge.

Engineering knowledge refers to the personal and public *know-how* and *know-that* which informs design engineers with the capacity to make relevant decisions and adopt appropriate courses of action in the course of designing an (Wang et al., 2007; Brunsmann & Wilkes, 2009). A classification of such knowledge is presented by Ahmed et al. (2005), as shown in

Table 1-1 below. All the different kinds of knowledge are undoubtedly important and represent valuable resource to any company (Brunsmann & Wilkes, 2009). However, it is the explicit knowledge (explanations about the design process and product) which is the most critical in a situation where we want to improve the explanation of design solutions. The problem often encountered by many design engineering companies is that even with the most advanced computer-aided design tools, the design process typically ends with a specification of the design but with little or no indication of the design choices that were made and the engineering knowledge that influenced the decision-making process (see Figure 1-1).

Table 1-1: Classes of knowledge and information in engineering design (Ahmed et al., 2005).

	Shared externally	Stored internally in human memory		
	Information	**Explicit knowledge**	**Implicit knowledge**	**Tacit knowledge**
Process	Descriptions of the design process (e.g. information)	Explanations about the process (e.g. rationale)	Understanding about the process (e.g. strategies)	Intuition about the process (e.g. insights)
Product	Descriptions of the product (e.g. information)	Explanations about the product (e.g. rationale)	Understanding about the product (e.g. relationship)	Intuition about the product (e.g. insights)

The problem often encountered by many design engineering companies is that even with the most advanced computer-aided design tools, the design process typically ends with a specification of the design but with little or no indication of the design choices that were made and the engineering knowledge that influenced the decision-making process (see Figure 1-1). This is because the various systems have no means of recording the associated design knowledge. It is also not always possible to rely on engineers who worked on particular projects to recollect the relevant engineering knowledge behind their design solutions. As observed by Ahmed et al. (2005), in the future, there are likely to be fewer opportunities to talk to the experienced designers and technology experts who were involved in past projects owing to employee mobility, retirement or merely forgetting the critical knowledge after a period of time. Consequently, the knowledge and reasoning that helped to shape the original design are lost rather than being passed on from one project team to the next.

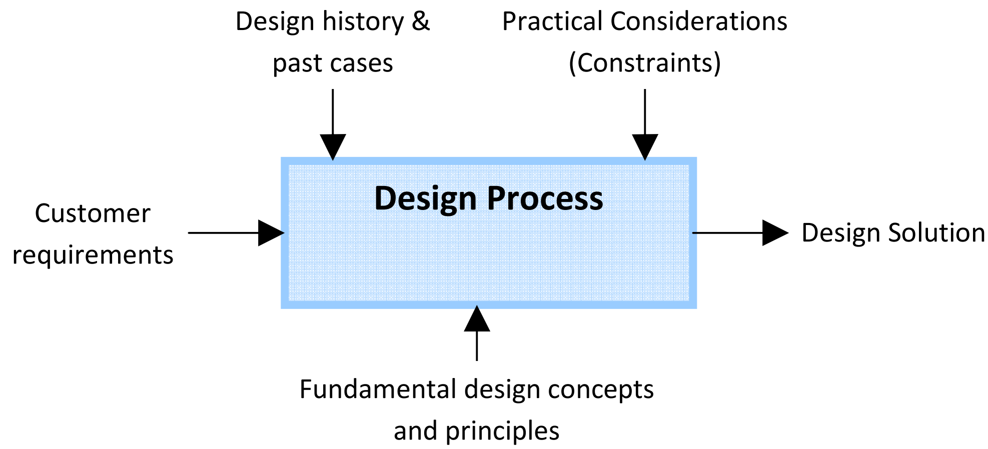


Figure 1-1: Design and Design Knowledge (Li et al., 2001).

The end result is that we end up knowing what was designed, but often have no idea why it looks the way it is, what motivated the particular design, what other design options were considered and rejected, what tradeoffs were made and their corresponding argumentation or justification, as well whether or not all specified requirements or desired features are met by the design solution. Considering the fact that the average lifespan of an aircraft is 20-30 years, this situation poses serious challenges later on especially for maintenance (sustaining) engineers who at one time or the other have to redesign parts of an aircraft component or carry out repairs due to a lack of a deep understanding of the original design.

Design engineers, thus, tend to reinvent the wheel, blindly treading the same paths where previous teams have been, often leading to poor project performance in terms of costs and lead-time. To effectively deal with the challenges of increasing complexity and competition, aerospace companies need to capture the knowledge which is available within their processes and make them more accessible. In this project, we employ design rationale as a useful knowledge sharing initiative to capture the essential knowledge that is created along with final design solutions to enhance the explanation of the design choices behind that solution to other design engineers or clients.

While there are different perspectives of this concept (Moran & Carroll, 1996), design rationale (DR) generally refers to a description of a design solution that goes beyond the record of its specification and testing, to include details of the reasoning and justifications of the decisions or design choices that have been made in the design process. It embodies knowledge on why an was designed to look or operate in one way rather than another, what trade-offs were made, what motivated the designer to include certain features and drop others as well as what mistakes or errors and lessons that were learned along the way. Ultimately, design rationale represents an *explanation* of why a particular design looks the way it does. DR has been identified as an invaluable aid for revising or modifying, maintaining, documenting, evaluating and learning the design (Dillon, 1997; Lee, 1997; Bracewell et al., 2009).

1.3 Problem Domain

The initial problem for this research project is stated, in a rather solution-oriented manner, as to 'develop a method to capture the rationale that has been put into aerospace parts designs during the design phase.' To uncover the underlying roots of the problem, a problem identification and investigation exercise has been carried out within the company. The central question that motivated the exercise is:

What are the problems and challenges associated with the lack of design rationale for projects at Fokker, and what are the anticipated opportunities and benefits to be derived from efforts to capture such knowledge?

The next two sub-sections describe the two stages of the problem investigation exercise. First section 1.3.1 describes an initial brainstorm session (group interview) with knowledge engineers, after which section 1.3.2 summarizes the major findings of interviews with some identified stakeholders. Finally, Section 1.3.3 analyses the varied stakeholder perspectives from the study findings and sets out the problem statement.

1.3.1 Group Interview: Knowledge Engineers

First an unstructured group interview session was held with knowledge engineers at Fokker to explore the reasons behind the idea to capture design rationale. This session was useful in identifying potential benefits of capturing design rationale based on an initial goal analysis (see

Figure 1-2 below), as well as helping to point out relevant stakeholders to provide deeper insight on the problem domain. The need to understand the problems from the perspective of the various stakeholders triggered the second stage of the process (this is documented in section 1.3.2).

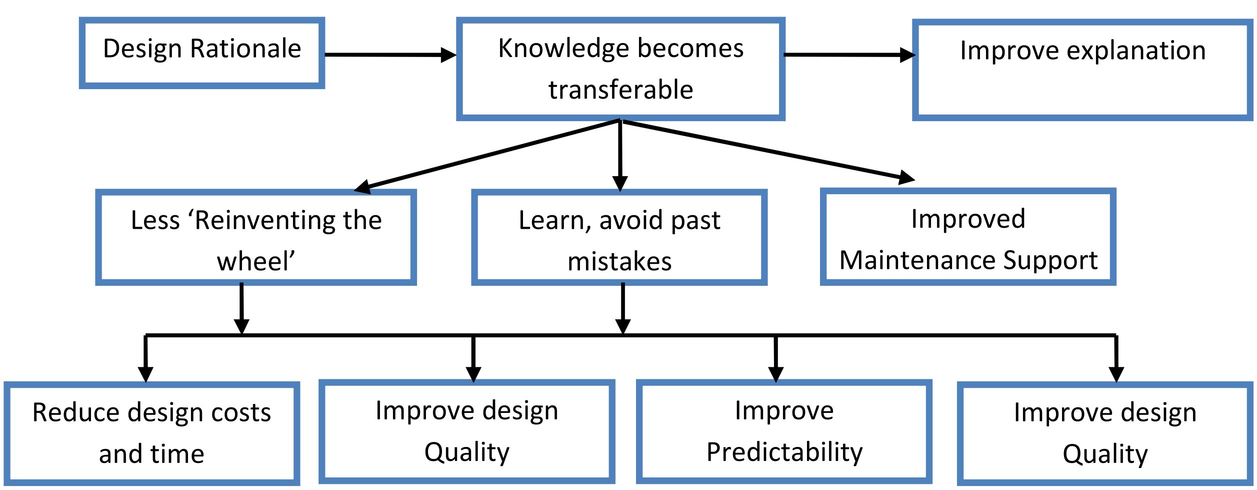


Figure 1-2: Goal Analysis – Capturing Design Rationale

By definition, a stakeholder refers to "individuals and organizations who are actively involved in the project, or whose interests may be positively or negatively affected as a result of project execution or successful project completion" (Cleland, 1988). A stakeholder can also be interpreted as a person who experiences a problem, or who is impacted by reducing it (Wieringa, 2008). We expect that identifying the right stakeholders and analyzing their concerns and needs will have a positive impact on reaching the initial desired goals. This expectation is justified since these stakeholders have first-hand experience and knowledge of the core problems that arise due to the lack of adequate design rationale and could offer useful insights in addressing the problems. Stakeholders were identified by examining the primary aircraft component development process of Fokker (shown in Figure 1-3 below).

The process starts with a proposal preparation phase through the Design Requirements Analysis and Design Definition until the Full scale development phase. This entire process is an iterative one which involves the close cooperation of actual design engineers (who create the Computer-Aided Design-CAD definitions) as well as stress, manufacturing, cost and weight engineers. Also closely involved are program and configuration managers who steer the entire project and Compliance verification and certification staff who ensure that the final product meets the initial defined requirements, and monitor safety and reliability issues. After a successful full scale development of the component, all maintenance responsibilities are transferred to Sustaining Engineers. In addition, clients and airline operators are potential stakeholders who stand to gain from the benefits of an improved design process as well as benefiting from design rationale itself as a tool for communicating with the design team.

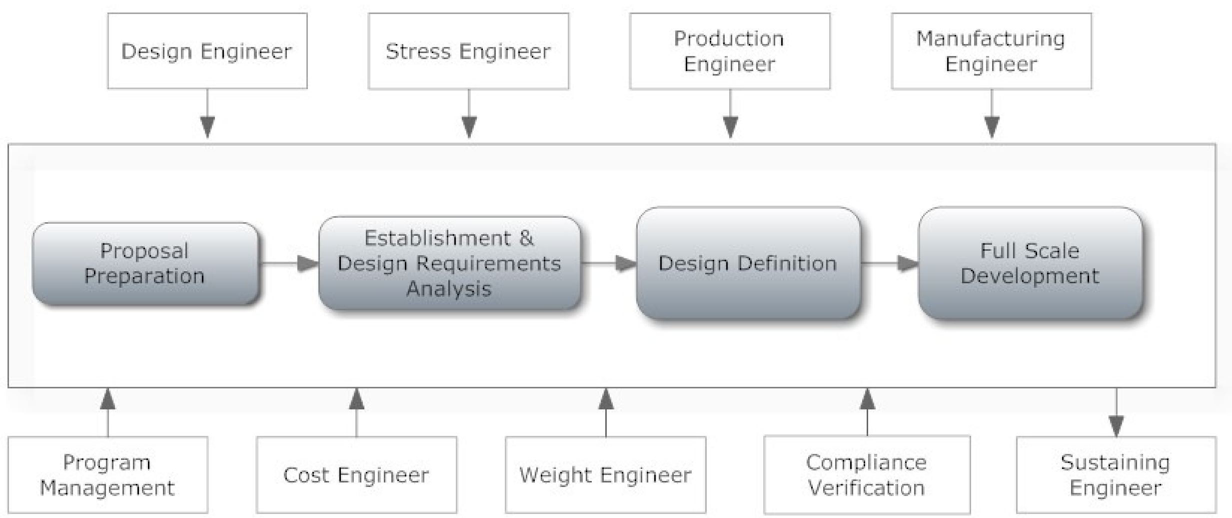


Figure 1-3: Stakeholders involved in the Aircraft Design Process

Other stakeholders such as Materials and Processes and Procurement and Supply are also actively involved in the aerospace component manufacturing process but these were not interviewed as focus was placed on stakeholders who are involved directly in shaping the final product. For full details of this group interview, including the methodology and process, see Appendix A.1.

1.3.2 Stakeholder Interviews

The second stage of the problem investigation process involved semi-structured interviews with (some of) the stakeholders identified in the group interview described above. The interviewees were mainly design, stress and weight engineers at Fokker with considerable project experience. For repeatability, the methodology and full description of the interview process can be found in Appendix A.2. The rest of this section presents a summary of the major findings from the interviews which do well to put the problems in perspective. Table 1-2 at the end shows specific goals and concerns elicited from the various stakeholders that were interviewed.

Existing means to capture (any form of) design knowledge

The interviews revealed that there is, at the moment, no widely-used means of capturing any form of design knowledge or rationale at Fokker. Some projects/engineers made attempts to capture rationale for design decisions using various methods while others did not document such knowledge at all. Interviewees mentioned personal notebooks, personal memory, design guidelines/Design Description Documents, and Change Request Documents useful means of recording the reasons that motivate design choices, but pointed out the difficulties of relying on them to keep track of design rationale. For example, design guideline documents are created at the beginning of a project to outline the major design choices to be made and the justification for the decisions. However, in the course of the project the design choices change due to the discovery of new requirements or constraints but the documents are not modified to reflect the new developments mainly due to higher priority of completing the project itself within time and budget. The last observation suggests that any design rationale capture method must be aimed at recording relevant rationale as a by-product of the design process.

Challenges due to the lack of design rationale

The biggest problems associated with the lack of design rationale capture at Fokker manifest themselves mainly in projects that demand the redesign of (parts of) existing aerospace components. Such projects are often necessitated by the detection of flaws in the original design that make the resultant component prone to damage, for example the Rib 7 bracket of a large commercial aircraft; or the need to build on existing designs to develop a new generation of that specific component or aircraft, for example modifying the design of the floor bed of a model of a business jet aircraft to suit the requirements of its successor. Another example is the redesign of the original model of a helicopter to introduce a sliding window in a different location.

In all these instances, engineers believed that the absence of design rationale from past projects often led to slower pace of new projects especially at the start where attempts are made to gather the relevant design knowledge and understand the relation between past and current requirements. At this point, various engineers involved in the project would want to know which problems and questions were faced by the past project teams and how they were overcome to better address the current issues. The inability to obtain this critical knowledge often leads to repeating past mistakes and reinventing the wheel, amidst other problems which collectively results in lower than desired project performance levels. This fact is evident in a statement from the design lead of the business jet floor bed-redesign project.

"We had to redesign the floor panels on the cabin floor for the new aircraft based exactly on the design of the old model: Same design, same material. But looking at the past drawings we had no idea why they made certain choices, and there wasn't any document to help explain this to us. In some cases we had to reverse-engineer, more or less, certain design choices. And sometimes we thought ah, that isn't a good choice let's do it this way and then they manufactured it and then we will find out quite late that it isn't such a good idea after all so we had to do it just like it was done in the past. When there is no document explaining the design choices you sometimes think 'I have a much better idea than they had' …but often that's not true. And usually you find out at a later stage of the process like making the detailed design or even manufacturing. This really made it difficult for us especially at the start of the project and we ended up taking much more time than necessary."

Overall, the stakeholders were of the view that capturing design rationale would bridge the knowledge gap between current and future projects as well as the communication gap between the different stakeholders. Major benefits from design rationale include the reduction of lead-time and project costs as improved decision-making during the project ensures a more efficient design process.

Table 1-2: Specific Stakeholder Goals and Concerns

No	Stakeholder	Concerns	Goals
1	Program Management	C1. Less than desired cost and time performance C2. Non-existent best practices/standard solutions	G1. Improved Key Performance Indicators (KPIs) G2. Improved design process for competitive advantage
2	Design Engineer	C3. Reinventing the wheel C4. Repeating past mistakes C5. Finding relevant design knowledge takes too much time	G3. Access previous design knowledge and reuse standard solutions/best practices G4. Improved communication with stress and manufacturing engineers
3	Stress Engineer	C6. Need to fully understand design solutions ensure it meets stress requirements/ opportunities for improvements	G5. Improved communication with design engineers
4	Weight Engineer	C7. Lack of understanding of design solutions makes it difficult to predict future design weights	G6. Enhance weight estimation based on improved understanding of reference design solutions
5	Manufacturing Engineer	C8. Need to fully understand design solutions to assess their manufacturing feasibility/opportunities for improvements C9. Designer needs to take 'manufacturing-friendly design principles' into account	G7. Improved communication with design and stress engineers G8. Improved understanding of specified design solutions
6	Compliance verification & Certification	C10.No easy/optimal way to verify design requirements	G9. A way to verify design solution against those requirements
7	Sustaining Engineer	C11. Difficulty in understanding design choices and associated reasons	G10. Able to understand/explain original design solutions since they are the baseline for maintenance work
8	Client	C12. Ensure design definition meets intended requirements; delivered on time and on budget.	G11. Compliant aerospace component (also, see 6)
9	Airline Operator	C13. Maintenance issues	G12. Lower maintenance cost (also, see 7)

1.3.3 Problem Statement

To formulate a problem statement for this thesis the initial goal analysis as well as feedback from interviews were analysed to identify root causal factors of concerns that were raised. In particular the concerns and goals of the various stakeholders were examined to established causal relations between the various concerns that were expressed. Figure 1-4 shows the resulting problem diagnosis, indicating the specific concerns and goals for which causal relationships were found.

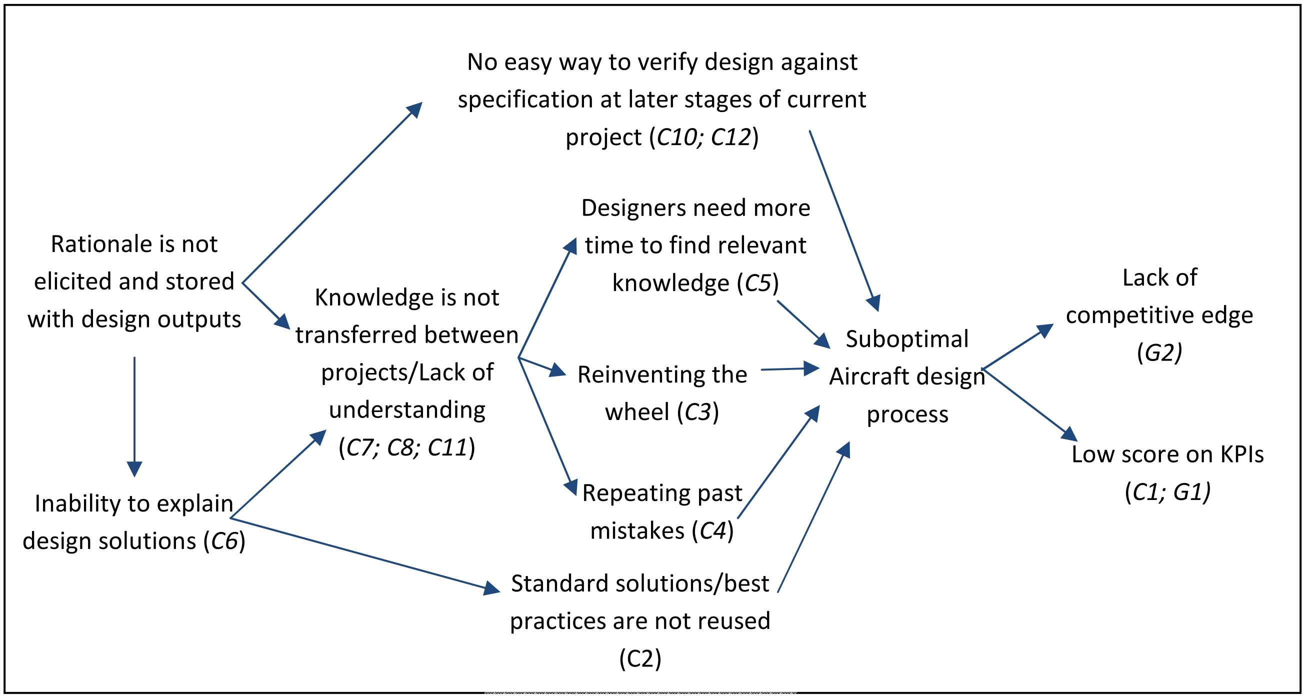


Figure 1-4: Problem tracing to research topic

As shown in the figure, an experienced problem for program management is the low score key performance indicators (KPIs) of the design process. This means there are concerns about critical indicators such as cost, lead time and product quality. The ultimate goal is to improve these performance indicators and enhance the competitive advantage of the company. The problematic phenomenon is caused indirectly by several undesirable conditions that persist in the course of product design. These include the relatively extended time taken by designers to find relevant knowledge to solve design problems, along with frequent cases of reinventing the wheel and repeating past design mistakes. Also, the lack of standard solutions and best practices which can be easily deployed, as well as a systematic means for verifying whether design solutions meet initial customer requirements both contribute to this situation. The collective effect of the undesired conditions is a sub-optimal aerospace component design process, which is actually the direct cause of the low KPI scores (though no stakeholder mentioned this). The listed undesirable design conations are also the effect of the situation where knowledge is not transferred between projects which can eventually be traced to the fact that knowledge about the design process and product (or rationale) is not captured and stored during the design process. By addressing this core problem we expect that the effects will lead to the achievement of the related goals of the stakeholders. This analysis results in the problem statement for this thesis.

Problem statement:

How best can the rationale that goes into the design of aerospace component be captured in order to improve the explanation of the designs?

This question raises several research issues. One important issue is *what exactly must be captured and stored as rationale as well as how to document the captured rationale.* The problem statement, and related research issues motivate the research questions to be addressed in this thesis.

1.3.4 Study Objectives and Conceptual Framework

To address the problem statement the study reported in this thesis aims to develop a method to capture design rationale to improve the explanation of design solutions. Research perspectives in capturing design rationale cover three distinct areas: capture methods for acquiring the rationale from domain experts, representation schemes for recording the captured rationale, and retrieval methods to facilitate the use of the documented rationale (see Figure **1-5**).

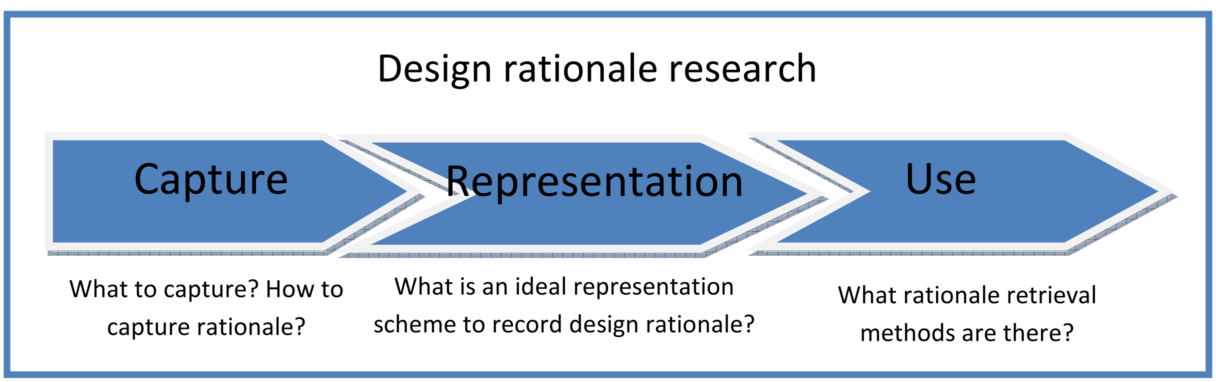


Figure 1-5: Issues in Design Rationale Research

It is important to note the dependencies that exist between the major research issues noted above. The first step in developing a method to capture design rationale is to first determine what exactly to capture but this decision depends on what we want to do with design rationale (Lee, 1997; Burge & Brown, 2000). Furthermore, the representation scheme that is adopted to record the rationale also puts a limitation on the content (Lee, 1997). It is only when the content and the schema are known that we can apply a suitable rationale acquisition method to capture the rationale. These dependency relationships are illustrated in Figure 1-6 below.

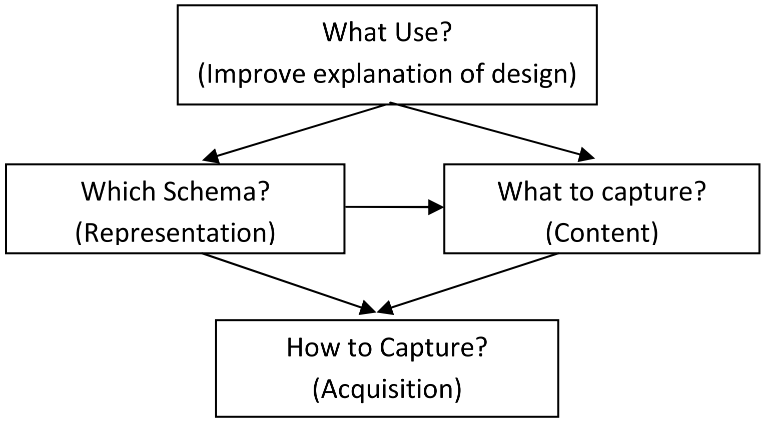


Figure 1-6: Framework for research to capture design rationale.

This research framework helps to scope and define the sub-goals of the research project. Given that what we want to do with design rationale is to improve the explanation of designs, the first sub-goal is to determine what specifically should be captured as rationale (content). To achieve this, the first step is to understand the concept of design explanations and define the key issues or the relevant questions that need to be answered to successfully explain design solutions. With the specified content as a set of requirements, the next sub-goal is to select or derive a suitable representing schema that is capable of recording the rationale. This is also to be tackled by investigating current methods of capturing design rationale and evaluating them against the criteria defined by the first sub-goal.

Finally, a method for capturing design rationale is proposed on the basis of the content and the representation schema.Figure 1-7 depicts the conceptual framework of this thesis. It posits that making efforts to capture design rationale during the design process can positively influence the successful explanation of the resulting design solution. Further, it indicates that the successful capture of relevant design rationale is itself influenced by two critical factors: the expressiveness of the representation scheme that underlies the design rationale capture method (effectiveness) and the usability of the method (efficiency).

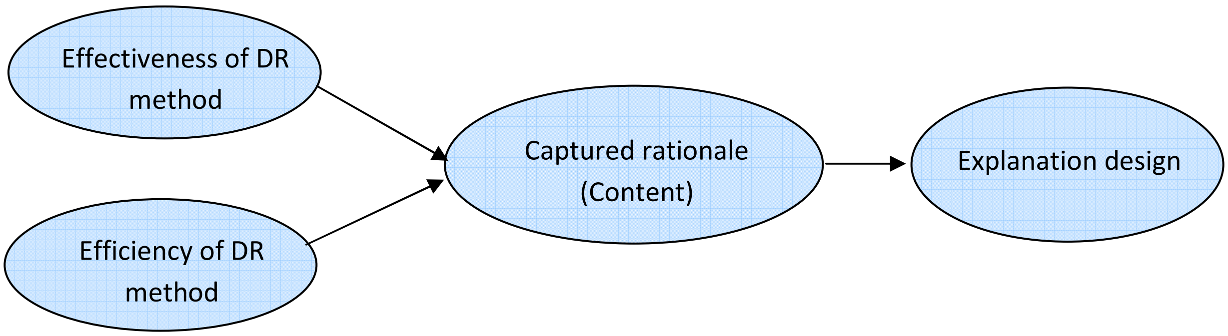


Figure 1-7: Thesis conceptual framework

1.4 Research Methodology

1.4.1 Research in Information Systems

As pointed out by Hevner et al. (2004), research in the information systems (IS) discipline is characterized by two paradigms: behavioural science research and design (science)[1] research. The behavioural-science paradigm, on one hand, seeks to develop and verify theories that explain or predict human or organizational behaviour. The design-science paradigm, on the other hand, aims to extend the boundaries of human and organizational capabilities by creating new and innovative s. While noting that both paradigms are fundamental to the IS discipline it has been well established in the literature that a design research approach produces findings that are relevant for solving practical (organizational) problems while still adhering to rigorous academic or scientific standards (e.g. Hevner et al., 2004).

This stems from the fact that design research aims to make use of existing knowledge and theory to construct 'better IS-related problem solutions' that improves some situation (Simon, 1996; Winter, 2008; Kuechler, & Vaishnavi, 2008). This research project follows the design research approach for the exact aforementioned reason. It is anticipated that adopting a design research perspective will ensure an effective and rigorous method for achieving the objectives of this research project, ensuring that we combine a high level scientific rigour with a high level of relevance for design work at Fokker Aerospace. The DSRP is embedded in Hevner's general Information Systems Research Framework (see

[1] Design Science, design research and design science research are all used in the literature. However, design research is used in the rest of this report since this research project is aimed at developing and evaluating a *specific* artifact, a design rationale capture tool as opposed to reflecting on *generic* solutions which is designated as design science Winter (2008).

Figure 1-8) to serve as the guiding methodology for this research project

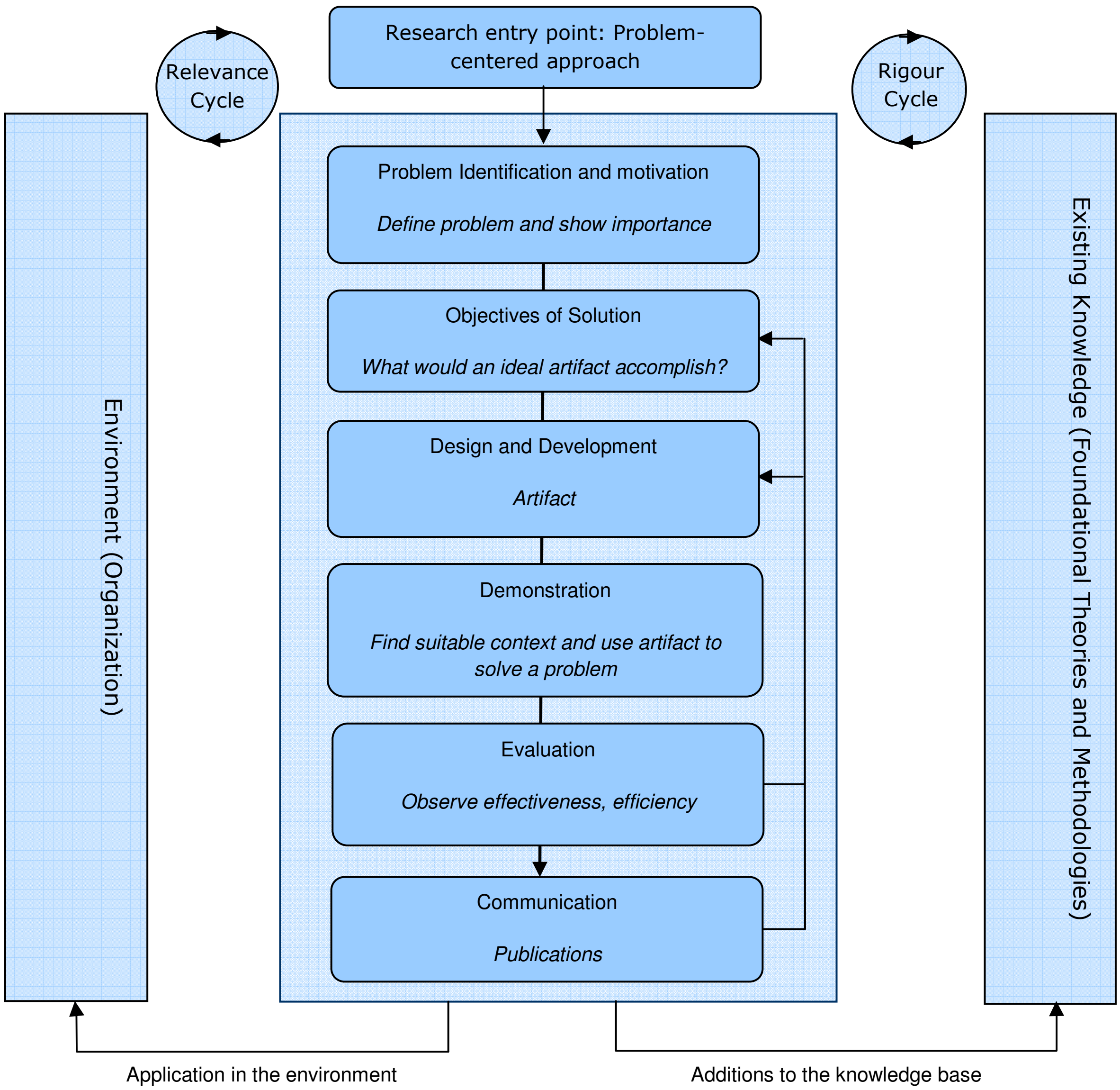


Figure 1-8: Design research process model (adapted from Peffers et al., 2006 and Hevner, 2004)

Hevner (2004) has identified seven clear guidelines for understanding, executing, and evaluating design-science research. As described above, we assume that the extent to which these guidelines are followed in this research process also says something about the validity of this research. The research process described in this thesis is later evaluated on the basis of this set of guidelines (see chapter 6). According to the authors, the purpose of the seven guidelines is to assist researchers, reviewers, editors, and readers to understand the requirements for effective design research; and further argue that each of these guidelines should be addressed in some manner for design-science research to be complete. Essentially, the guidelines identify key aspects of a design research which must be addressed.

Table 1-3: Design Research Guidelines (Hevner, 2004)

Guideline	Description
Guideline 1: Design as an	Design-science research must produce a viable in the form of a construct, a model, a method, or an instantiation.
Guideline 2: Problem Relevance	The objective of design-science research is to develop technology-based solutions to important and relevant business problems.
Guideline 3: Design Evaluation	The utility, quality, and efficacy of a design must be rigorously demonstrated via well-executed evaluation methods.
Guideline4: Research Contributions	Effective design-science research must provide clear and verifiable contributions in the areas of the design , design foundations, and/or design methodologies.
Guideline 5: Research Rigor	Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design .
Guideline 6: Design as a Search Process	The search for an effective requires utilizing available means to reach desired ends while satisfying laws in the problem environment.
Guideline 7: Communication of Research	Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences.

1.4.2 Research Questions

With the main objective of the thesis being to capture design rationale to improve the explanation of design solutions as a possible means to address the problem statement, the central research question to be answered in this thesis is: *What is a useful method to capture design rationale to improve the explanation of design solutions?* To operationalize this question, several specific sub-research questions are formulated as described below.

Since capturing the design rationale is the main approach taken to address the problem statement, it is important to first understand design rationale as a concept and its relations with other concepts such as the nature of design and explanation. This is to create a theoretical background for the research. Thus, the first set of associated research questions are as follows:

A. What is design rationale?
   1. What DR capture approaches are there?
   2. What do the DR methods aim to capture and how are they documented?
   3. What are the benefits and success criteria for methods to capture design rationale?

The next set of associated research questions address the nature of design, especially within the aerospace domain and attempts to derive a theoretical model for explaining design solutions. The purpose of the model is to serve as requirements for the design rationale capture method.

B. How can design solutions be explained?
   1. What is design?
   2. What is the nature of the aerospace design domain?
   3. How can existing explanation theories be applied to the design context?

Both Questions A and B are answered mainly by literature review but also through a study of some Fokker design documents and interviews with experienced design and knowledge engineers. Based on the theoretical foundations and requirements for design explanation, the next questions are aimed at developing a framework for a design rationale capture method.

C. What is a suitable method to capture design rationale for design explanation?
   1. What are the key functional and non-functional requirements?
   2. What exactly must be captured as rationale?
   3. How should the captured rationale be documented?
   4. What suitable methodologies/design tools for realizing and exploiting design rationale capture method exist?

Finally, the method is evaluated by accessing its efficacy in practice.

D. Is the derived design capture method valid and useful in practice?
   1. Can the rationale captured by the method explain designs (effective)?
   2. Is it efficient?

Is the research process valid?

The research methods to address these questions are shown in Table 1-4.

1.4.3 Research Methods

Table 1-4: Research questions and methods

Research Stage	Research Question	Research Method	Thesis Chapter
Problem Identification and Motivation	A. What are the problems at Fokker Aerospace due to the lack of design rationale? 1. What are the challenges and anticipated benefits?	Survey (Interviews)	1
Objectives of Solution (Foundations/ Theories)	B. What is design rationale? 1. What DR capture approaches are there? 2. What do the DR methods aim to capture and how are they documented? C. How can designs be explained? 1. What is design? 2. What is the nature of the aerospace design domain? 3. How can existing explanation theories be applied to the design context?	Systematic Literature Review Fokker Design Documents	2,3
Design and Development (Design Methodologies)	D. What is a suitable method to capture design rationale for design explanation? 1. What are the key functional and non-functional requirements? 2. What exactly must be captured as rationale? 3. How should the captured rationale be documented? 4. What suitable methodologies/design tools for realizing and exploiting design rationale capture method exist?	Systematic Literature Review Fokker Design Documents	4 5
Demonstration/ Evaluation	E. Is the derived design capture method valid? 1. Can the rationale captured by the method explain designs (effective)? 2. Does it require (efficient) 3. Is the research process valid?	Case Study/Workshop Focus Group Discussion/Review Survey	6

2 Explaining Aerospace Design Solutions

Knowledge is the object of our enquiry, and men do not think they know a thing till they have grasped the 'why' of it.

- Aristotle (Physics, II.3.194B17; II.3.194B31)

2.1 Introduction

This chapter begins an investigation into the theoretical foundations upon which this thesis is based. The aim here is to derive a theoretical explanation model that is capable of improving the explanation of design solutions. The conceptions of design (solution) and explanation that will be used in later chapters are also defined. The rest of the chapter is structured thus: Section 2.2 introduces the aerospace design domain, first taking a look at the concept of design in general, and ending with an overview of the aerospace design process. Next, section 2.3 discusses the challenges for explanation of design solutions. Section 2.4 then reviews major theories on explanation from literature which are later applied to the aerospace domain in section 2.5 to derive content requirements for a comprehensive and satisfactory explanation of designs. Finally, section 2.6 concludes the chapter with design explanation model based on the analysis presented in all the sections. **Figure 2-1** below illustrates the overall structure and framework of the chapter.

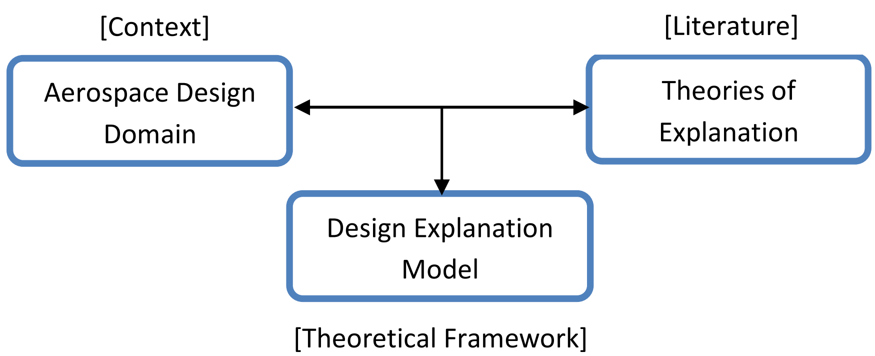


Figure 2-1: Framework for this chapter

2.2 Exploring the Aerospace Design Domain

The word design has such diverse applications, even in everyday life, that its meaning is not always straightforward. *Design* can be used as a verb, a noun and an adjective; and can either refer to the development process of an , the itself, primarily its functionality, and yet it might even refer to the gloss on the finished product. Thus design connotes aesthetics, ergonomics as well as functionality. A formal definition of design is offered by the International Technology Education Association[2]: 'an iterative decision-making process that produces plans by which

[2] Available online at http://www.iteea.org/TAA/Resources/TAA_Glossary.html [last accessed on 25 may, 2010]

resources are converted into products or systems that meet human needs and wants or solve problems'. Visser (2004) also sees design as 'an activity consisting in specifying an , given requirements that indicate one or more functions to be fulfilled and/or objectives to be satisfied by the '. These two definitions are consistent, and portray the perspective of design that is adopted for this thesis. The concept design solution is used hereafter to refer to the end product of the design process, which in the aerospace engineering domain is always some form of a CAD definition.

Design is, at its heart, a constant problem-solving and decision-making process. This fact holds whether engineers are designing an aircraft, architects are designing a building, or software engineers are designing the software to control a manufacturing process (Burge and Kiper, 2008). Design, thus, covers a range of different activities in various domains: engineering design, architectural design, software design etc. As stressed by Moran and Carroll (1996) design activities involved in these various domains have much in common and can be characterized as a goal-oriented, constrained, decision-making, exploration, and learning activity that operates within a context that depends on the designer's perception of the context. The activities in all domains follow a general design process as illustrated in **Figure 2-2**.

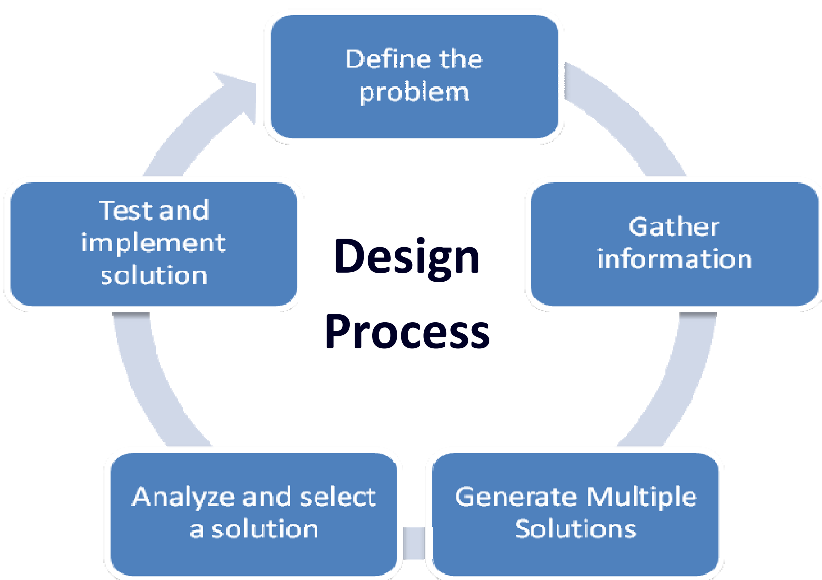


Figure 2-2: Generic Design process (Khandani, 2005)

The process starts with a definition of the problem to be solved. This problem can be created by some specific customer requirements or constraints that are to be satisfied. Typically in the course of the design process, designers are faced with several alternatives from which to choose in solving the problem at hand. Design decisions, which are essentially responses to problems or opportunities faced by designers, are made on the basis of arguments which support or contradict the defined alternatives. Navigating the maze of problems, opportunities, decisions, alternatives, and arguments to arrive at a final solution is what makes design a decision-making process (Bevan & Macleod, 1994; Burge and Kiper, 2008).

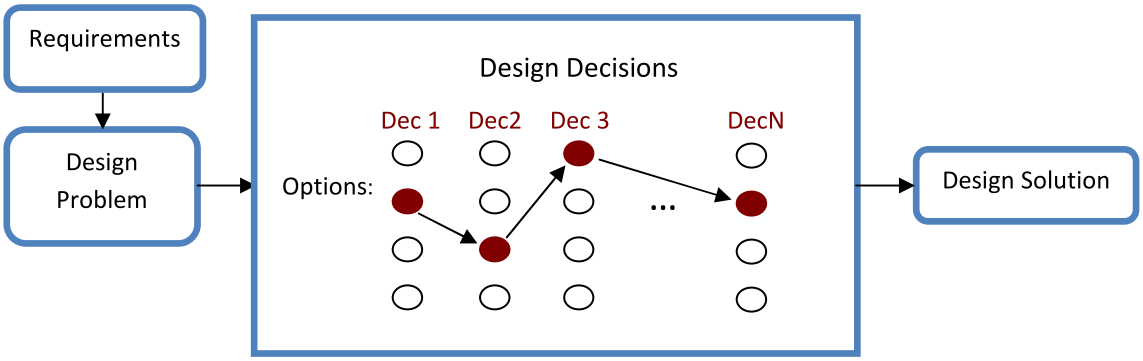


Figure 2-3: Creating design solutions: constant decision

At Fokker Aerospace where this research was carried out, Figure 2-4 below represents the overall high-level process of manufacturing an aerospace component. The process begins with preparation of proposals that seek to secure the project from the various clients, after which design requirements are established and analyzed. This kick-starts the design definition phase leading to the full scale development of the component. While many activities occur within these phases, such as writing proposals, identifying the right production materials and manufacturing, the focus here is on creating the actual design solutions based on the customer requirements.

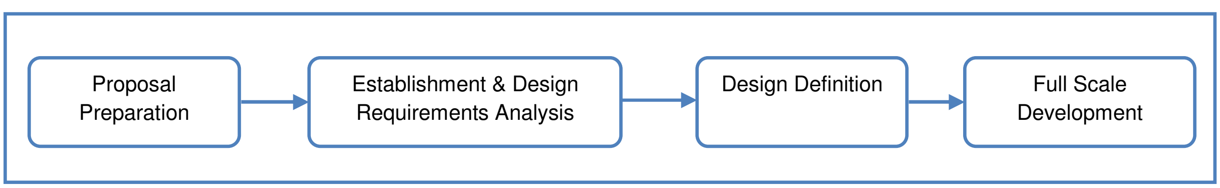


Figure 2-4: High-level Aircraft Design Process

Like all other design problems, aerospace design problems are complex and require diverse techniques to solve them. Some of these techniques include problem simplification, problem decomposition, and trial and error methods (Schut and Van Tooren, 2008). One often used technique is the problem simplification approach (see Figure 2-5 where the problem is broken down into three stages: conceptual design, preliminary design, and detailed design (Raymer, 2006; Schut and Van Tooren, 2008).

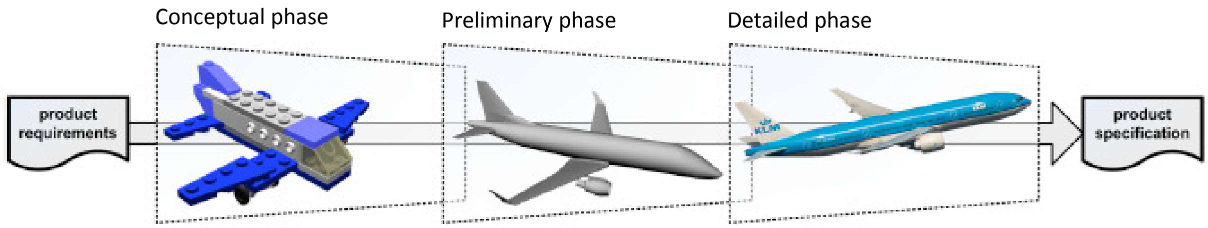


Figure 2-5: Phases of the aerospace component design process (Schut and Van Tooren, 2008)

Each of the stages involves similar activities with the major difference being the level of analysis of the input requirements as well as the level of detail of the output design solution. The activities, along with their input resources and output documents or s are shown in Figure 2-6. As indicated, the first activity is to collect the set of requirements to be satisfied by the solution. These may or may not be complete and are further refined during the design process. Based on an overview of the requirements, options are generated which are then validated against the requirements to ensure compliancy. The options are essentially *working principles* or concepts which are known to the designer as potential solutions for the problem at hand.

The identified options are then validated iteratively until all validation requirements are satisfied, in which case a trade-off analysis is carried out to assess all possible design solutions (referring to the options which were successfully validated). Very important for the trade-off analysis is a set of criteria which are specific set of critical requirements such as complexity, weigh, cost, etc which are chosen with respect to the component to be designed. A best solution is then selected as an output of the trade-off process by weighing the possible design solutions against the specified criteria. If new requirements are introduced due to the selected solution, which is most often the case, then entire process is revisited albeit at a higher level of detail and analysis.

It is important to note that Figure 2-6 reflects the activities that are carried out during the design process as well as the necessary documents that are generated in the process. Such conceptual entities as design problems posed by the requirements and constraints, arguments pros and cons for the options and criteria for selecting the best solution are not explicitly recorded in any way but are nonetheless important to track the reasoning that results in the outputs in the figure. The next section introduces these concepts in a model that is aimed at understanding what is meant by the explanation of design solutions.

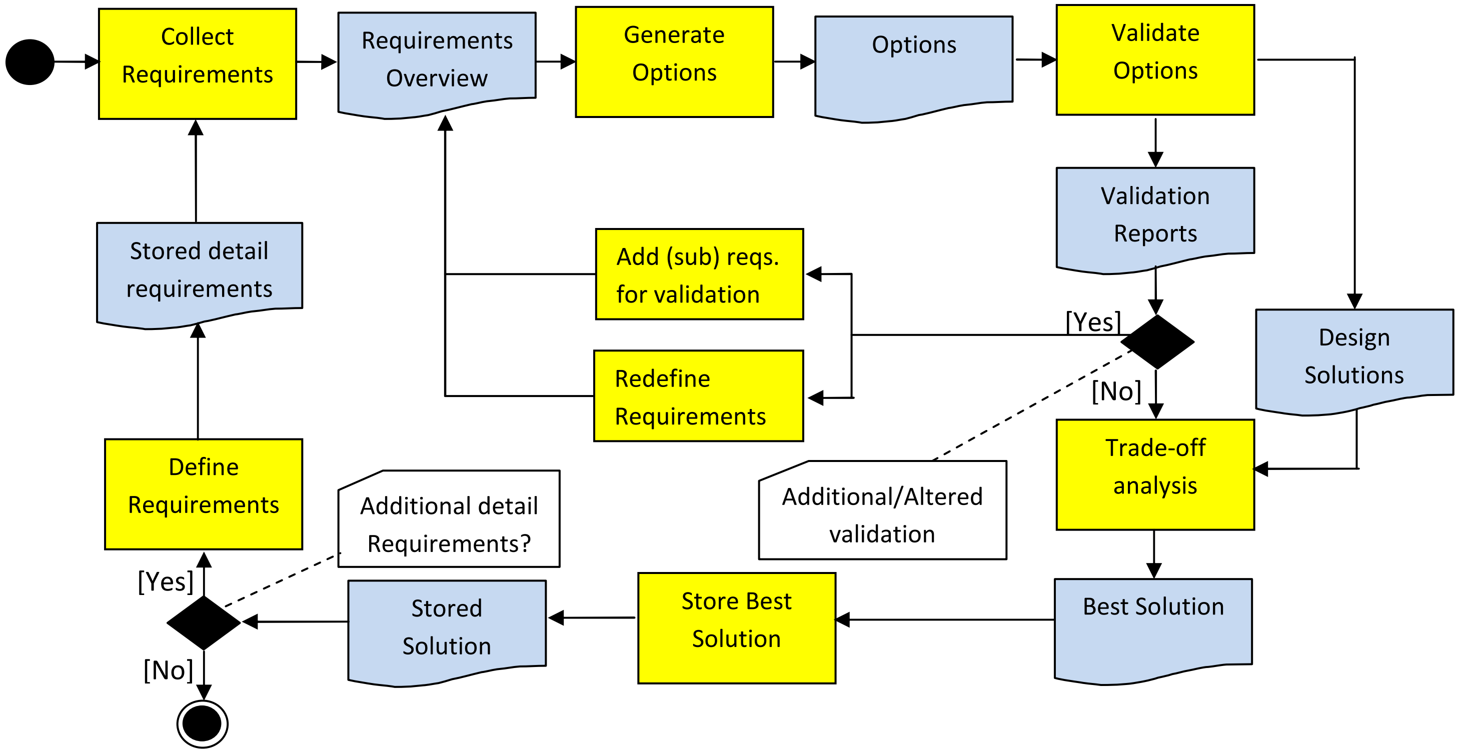


Figure 2-6: Aerospace component design process (observed at Fokker Aerospace)

2.3 Explaining a Design Solution

Why do fishes respire with gills rather than lungs? Why do tetrapods respire with lungs rather than gills? Why don't these organisms respire through their skin? These questions are discussed in many respiratory physiology biology textbooks and are often answered by showing that in the conditions that apply to the relevant organisms, the actual design is better than some other contrasting design (Wouters, 2007). Such discussions are not exclusive to biology. In aerospace design it is also often important to explain why a specific design solution looks the way it does. If a certain design solution is stored as the best solution we would want to know why that particular option was chosen over all other possible alternatives.

For example, consider the choice for a specific design of a flange (see Figure 2-7). If at some point it becomes necessary to redesign an aerospace component containing this flange design, we would want to know why option 2 was selected over option 1 and assess that decision in the light of possible new requirements or design insights. It is only through an awareness of the reasons and sound arguments behind such a choice that it (the design choice) can be explained and evaluated. A complete explanation of the (past) design solution facilitates a timely and cost-effective redesign and development process; and is also useful during periodic maintenance where the original designs are used as baseline for any possible repairs.

Design Concept (Option) 1 **Design Concept (Option) 2**

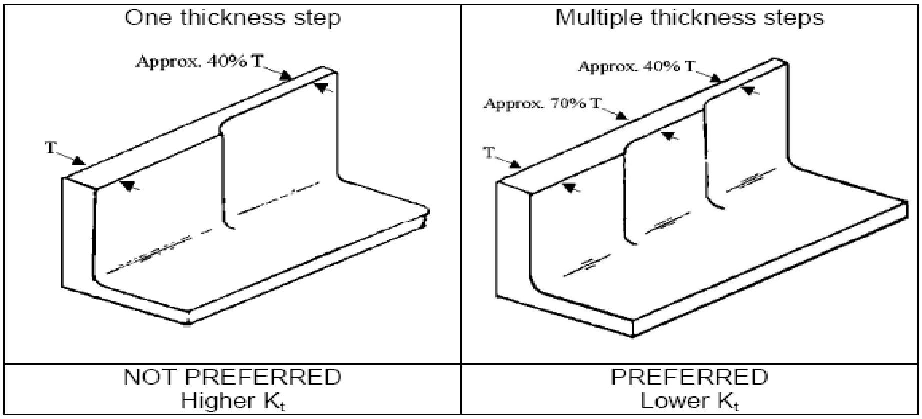


Figure 2-7: Options for the design of a flange (Fokker AESP, 2009)

As noted in the discussion of the design process, a design solution is the outcome of a multitude of decisions which are made in the light of the general purpose of the , its “context of use” (Bevan & Macleod, 1994) and connected trade-offs and arguments (Moran & Carroll, 1996). It is almost impossible for a designer to look at a design solution and envision all the design-driving information that helped to shape the design. It is this information that helps to explain how the design outcome was reached. Figure 2-8 below illustrates basic points of interest where explanations might be required within the framework of the aerospace design process already depicted in Figure 2-6.

Note that the concepts Design problem, Arguments and Criteria which are absent from the design process are introduced. The design problem represents a conceptual analysis or the design issues faced by a designer in trying to come up with solutions that satisfy the given requirements. Arguments, for or against, are statements which support or undermine options in the light of the requirements, whiles criteria refers to important selected sets of requirements against which to weigh all possible design solutions in order to select a best solution.

As shown in the figure, the basic questions which are required to be answered to explain the design outcome are of two types: why and why not? That is, *why* the particular options were generated, *why* the specific design solutions from the set of options, and *why* did we arrive at the specific best solution out of the possible design solutions; OR *why not* the other options which were not generated/selected and *why not* the other design solutions?

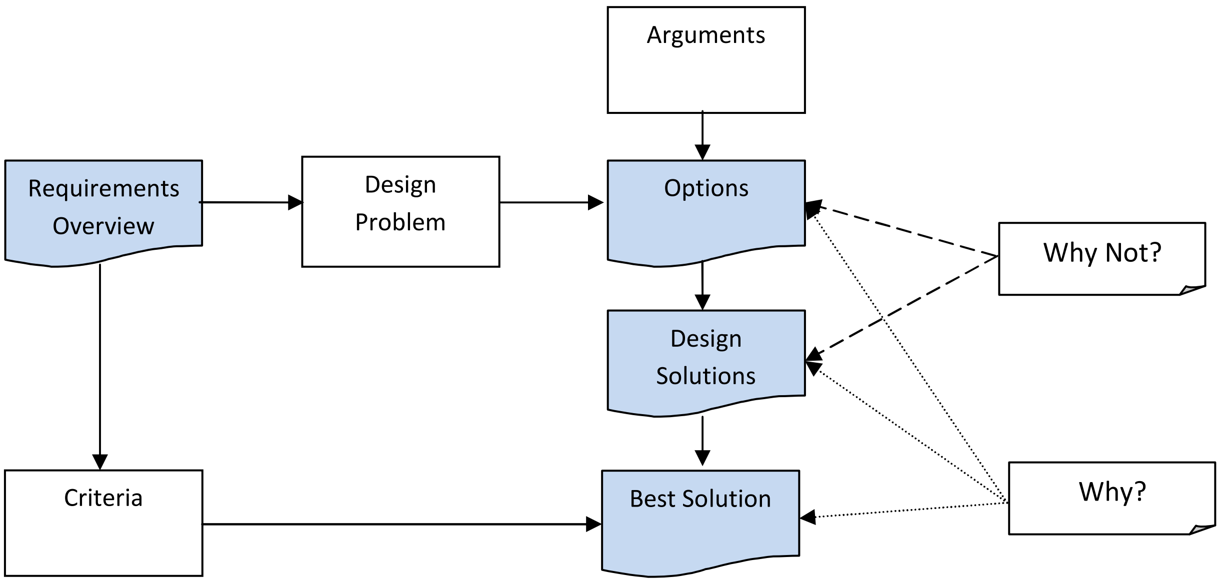


Figure 2-8: Basic points of interest in design explanation (what we want to explain).

To address how we can answer the why and why-not questions from a scientific perspective, the next section presents an overview of the major accounts of explanation from literature. This is in a bid to understand the very nature of an explanation, and to derive requirements for content which are necessary for providing explanations. The flange design example in Figure 2-7 is used as an expository example to clarify the analysis.

2.4 Accounts of scientific explanation

2.4.1 General Definition

It has often been noted that the word "explanation" is used in a wide variety of ways in ordinary English—we speak of explaining the meaning of a word, explaining the background to philosophical theories of explanation, explaining how to bake a pie, explaining why one made a certain decision (where this is to offer a justification) and so on.

The New Shorter Oxford English Dictionary defines explanation as:

1. The action or an act of explaining.

2. A statement, circumstance, etc., which makes clear or accounts for something.

3. A declaration made with a view to mutual understanding and reconciliation.

As pointed out by Haynes (2001), this dictionary definition, in spite of its clear indication of what the goals of explanation are, hardly gives an idea as to what are the contents of an explanation or what kind of information it must convey. A good understanding of an ideal explanation is crucial in deriving a framework that describes how the essential elements of philosophical theories of explanation may be applied to the engineering design domain.

Discussion on scientific explanation dates back to pre-Socratic times; and yet, the question of what should be taken as an explanation is the subject of continuing investigation (Woodward, 2003). A thorough discussion on the ongoing debate on the definition and semantics of scientific explanations is not the main purpose of this section but rather to give an overview of the main accounts of explanation that have been proposed in the philosophy of science literature.

Perhaps the simplest definition of an explanation is that it is an answer (Fraassen, 1977); in particular an answer to why-questions (Schurz, 1995). They are intended to explain 'Why things happen – where the 'things' in question can either be particular events or something more general such as regularities or repeatable patterns in nature' (Woodward, 2003). However, explanation has always been thought to have more than one aspect. Aristotle, for instance, believed that why-questions could be answered by appeal to four kinds of causes, each providing insight into some aspect of the question (Lombrozo & Carey, 2006). This line of thought has spawned various theories of explanation which are all meant to answer the why-question but in a different way and requiring different input.

The subsequent sub-sections present an overview of the different classes or accounts of explanations that have been proposed and discussed in the literature. The idea is to discover the various ways of answering the why-question from the scientific perspective and derive implications for providing content for an explanation.

2.4.2 The Deductive-Nomological (DN) explanation

According to the DN account, an explanation is a logical argument to the effect that the phenomenon or event to be explained (referred to as the explanandum) was to be expected in virtue of certain explanatory facts which are the laws and initial conditions (the explanans) that characterize and precede the event. Several conditions must hold for a DN explanation to be true:

- the explanandum must be a logical consequence of the explanans;
- the sentences constituting the explanans must be true, and
- the explanans must contain at least one "law of nature" and this must be an essential *premise* in the derivation of the explanation.

Thus, a DN explanation is always a law-involving deductive argument. Specifically, a DN explanation shows that given the particular circumstances and the laws in question, the occurrence of the phenomenon was to be expected; and it is in this sense that the explanation enables us to understand why the phenomenon occurred. (Hempel, 1965, p. 337). The DN account is intended to capture the form of any deterministic scientific explanation of an individual event, such as the expansion of a particular metal bar when heated or the extinction of dinosaurs. Such an explanation is always deductive derivation of the occurrence of the event to be explained from a set of true propositions including at least one statement of a scientific law. Thus a deterministic event explanation is always a sound, law-involving, deductive argument with the conclusion that the event occurred.

Generally, a DN explanation is of the form:

Li (general laws)
Ci (antecedent conditions or facts)
_______________ (deductively entails)
∴ P (the phenomenon to be explained)

If the statements Li and Ci, which are the premises, are true then statement P is expected to occur. For example, consider the why-question:

Q: Why did Jan's bracelet melt when it was heated to a temperature of 1063° C?

A DN explanation to answer such a question is of the form as illustrated below:

1. Gold melts at 1063° C.	*law*
2. Jan's bracelet is made of gold.	*condition*
∴ Jan's bracelet melted at 1063° C.	*observed phenomenon*

It is evident from the definition and the above example that laws and law-like statements are central to the idea of a DN explanation and they play an important role in formulating justifications meant to answer why-explanation requests (Haynes, 2001). Laws are considered here to be a subset of true generalizations which are not just accidentally true (Woodward, 2003). An example of an accidentally true generalization is: *All the apples in my fridge are green;* while the statement: *All gases expand when heated* is a law. Thus, a law in the DN account is a "statement of universal conditional form which is capable of being confirmed or disconfirmed by suitable empirical findings" (Hempel, 1942). Although the DN account has been subjected to a number of criticisms especially on the questions of what exactly count as laws, and explanatory irrelevance of some conditions (Kitcher, 1981; Woodward, 2003); this approach represents a logical way of answering the why-question.

2.4.3 Functional Explanation

Functional explanations, also sometimes referred to as teleological explanations, attempt to provide arguments for the existence or persistence of entities (objects, events, or institutions) by reference to the effects, in most cases the beneficial effects, of those entities (Haynes, 2001). Thus, this perspective of an explanation accounts for the existence of things in terms of a function they perform. Functional explanations have mainly been used in Biology and the Social Sciences (Haynes, 2001; McLaughlin; 2001; Kincaid, 2007). For example, In Biology the question 'why do we have hearts?' can be answered by explaining that it is because they pump blood (Lombrozo & Carey, 2006). Similarly, functional explanations have been used to explain why certain social practices exist by reference to the purpose or needs they serve, e.g. the claim that the division of labor in society exists in order to promote social solidarity (Kincaid, 2007). Such arguments describing functional explanations are referred to as *function statements.*

The validity of function statements as true explanations are controversial with proponents pointing to the fact that things exist or events occur because of some *reasons*, and implying causal relations between some precursive event and the one to be explained. That is attempting to find causes of the events that lead to something being created, and causes of events leading to that something persisting. Among others, arguments against the idea of functional explanations include the lack of supporting evidence for the mechanisms by which certain features exist which means that functional explanations are not generally falsifiable since related specific evidence are often not identified (Haynes, 2001). In spite of this, functional explanations introduce another perspective of explanations which are especially relevant for engineered s and will be further discussed in relation to aerospace design (see section 2.5).

2.4.4 Pragmatic Explanation

Pragmatists hold that explanations should be considered good in so far as they effectively answer why-questions. Thus, what counts as a good explanation in a certain situation is dependent on some context-dependent criteria and not a normative, regulative model (such as the DN model discussed above) that defines adequacy criteria for an ideal scientific explanation (Cohnitz, 2000). Of particular importance to pragmatic theories of explanations are two central concepts: the role of *relevance relations* and *contrast classes* in the construction of an explanation. Van Fraassen (1980), a key proponent of the pragmatic explanation argues that:

"The description of some account as the explanation of a given fact or event is not complete. It can only be an explanation with respect to a certain relevance relation and a certain contrast-classes." (p. 130)

Relevance relations aim to describe events that relate to the event to be explained in terms of the relevance of those events to the purposes of the explanation (that is relevant events leading up to the particular event or thing to be explained). Contrast classes provide information on why a particular event occurred instead of, or in relation to, another in its contrast class.

For example, consider the why-question:

Q: Why is our flag still there?

This might be used to pose different questions depending on the contrast intended (Achinstein, 1984). For example, this could mean:

- Why is our flag (rather than some other flag) still there?
- Why is our flag still there (rather than somewhere else)?
- Why is our flag (rather than something else) still there? And so forth.

The contrast class consists of what is presupposed by the question (our flag being there) together with the alternatives (there being some other flag there, our flag being somewhere else, etc.). Hence, the contrast class is determined by considering the context of the question.

As regards relevance relations, the question might be construed as a request for the events leading up to the flag being still there, although another possible interpretation could be as a request for the function or purpose of our flag being there. According to the pragmatist view, what we need to know is *what "relevance relation" is being requested*--"events leading up to", "function", or something else. And this, as in the case of the contrast class, is also to be determined by looking to the context. "Looking to the context" could mean invoking the intentions, beliefs, and problems that that motivated the question; and this is pragmatic (Achinstein, 1984). This analysis confirms the pragmatist view that (van Fraassen, 1991):

“Which factors are explanatory is not decided by features of the scientific theory but by concerns brought from outside.

The notion of a pragmatic explanation is intuitively appealing. It confirms the idea of answering why-questions from different perspectives (eg. On the basis of functions or laws); and the concepts of contrast classes and relevance relations are particularly useful in explaining design solutions. This will be discussed shortly in section 2.5.

2.4.5 Rational Choice and Explanation of human action

Rational choice theories of explanation attempt to describe behaviour, in this case human behaviour, in terms of the perceived benefit of that behaviour relative to other possible behaviours (Haynes, 2001). Rationalizations can be viewed as an actor giving reasons to why a particular action was taken, and can be described as causal explanations: that is, under the premise that “the primary reason for an action is its cause” (Davidson, 1963). Central to this view is the idea that the primary reasons express the intention of the person performing the action. This description reflects a more general intentional explanation (Martin and McIntyre, 2004). Although intentions are important, rational-choice explanation goes beyond intentional explanation to insist that for a behaviour or action to be rational, it must be stem from desires and beliefs which can in themselves be described as rational.

An ideal satisfactory rational-choice explanation of an action would show that the action is the (unique) best way of satisfying the full set of the agent's desires, given the (uniquely) best beliefs the agent could form, relatively to the (uniquely determined) optimal amount of evidence (optimal part of the explanation). In addition the explanation would show that the action was caused (in the right way) by the desires and beliefs, and the beliefs caused (in the right way) by consideration of the evidence (causal part of the explanation). Put together, the two parts yield a first-best rational-choice explanation. The optimal part by itself yields a second-best explanation which for practical purposes must be sufficient in the light of the difficulties in determining psychic causality of the agent.

The ambiguities of the beliefs and desires that drive rationale-choice decisions have warranted attempts to fit human action to other forms of explanation. For example, applying the DN model to explain that human action is governed by laws (Ruben, 1998). In this thesis we conceive that the rationale choice explanation is influenced by all the other types of explanation described above. By definition a rational choice is the best way of achieving an actor's desires given the best beliefs relative to an optimal amount of evidence. Clearly, such evidence or beliefs and subsequent decision-making could be backed by laws (DN explanation) or relevance and other alternatives (Pragmatic explanation) or even based on the purpose or function of an alternative relative to the goal of the decision-making (functional explanation).

2.5 Applying explanation theories to Aerospace Design Context

Having reviewed four major explanation types, this section sets out to apply the theories to the aerospace design domain. The subsequent sub-sections take a look at each of the explanation types and present analyses of implications in the design context.

2.5.1 DN Explanation of Design

On the basis of the DN account of explanation (discussed in section 2.4.2), a DN explanation for a design solution would be an argument that states that on the basis of some initial conditions such as those relating to requirements and design goals, and some prevalent design related laws, the design choice leading to a particular design solution was to be expected. Haynes (2001) argues that 'laws play a role in IS explanation by relating design decisions and the resulting system structure to the physical laws, standards, norms, and other reasonably well established universals that both constrain and guide the design process.' This reasoning also holds for the aerospace design context although the laws may take different forms. Fundamental design principles, design guidelines and known standard solutions all play a role in explaining why certain options are generated to address specific requirements and why some of those options are further developed to arrive at a final solution.

1. Design Principles, Constraints, etc.	*Law*
2. Design Requirements, Goals	*Condition*
∴ Design Choices (solution)	*Observed phenomenon*

Consider the flange example, introduces earlier in section 2.3. A DN explanation for the choice of design option 2 will be formulated as follows:

1. A damage tolerant component has a lower stress concentration.	*Law*
2. A component with multiple steps has lower stress concentration.	*Law*
3. Design a damage tolerant flange.	*Condition*
∴ Solution: Choose Option 2 (flange with multiple thickness steps)	*Observed phenomenon*

The essentially translates to the argument that:

Given that (1) a damage tolerant component has a lower stress concentration, that (2) a component with multiple steps has lower stress concentration, and that (3) we want to design a damage tolerant flange (which is a component) then the choice for a flange with multiple thickness steps was to be expected.

This argument explains why Option 2 was selected, although the explanation itself makes no reference to the alternative Option 1. The DN explanation of a design thus requires knowledge of the initial design conditions, namely the customer requirements and goals; as well as an awareness of fundamental laws or law-like facts within the design domain which in one way or another influence or constrain design choices. A limitation here is being able to recognize and capture all relevant *design laws* that influence design outcomes. A further observation is that most of these constraints or law-like influences are usually translated into requirements to complement the initial customer defined requirements. For instance, safety or air worthiness constraints introduce requirements such as double-locking features for fasteners in movable aerospace components.

2.5.2 Functional Explanation of Design

The functional explanation of a design solution presents an argument that the design solution was realized as a result of its purpose or the functions that solution or a feature of it was supposed to provide. This class of explanations is especially relevant in the context of engineered s where it is assumed that human design activities are meant to serve some purpose (Haynes, 2001). Within the aerospace design domain, a specification of the functional requirements is the likely source of function statements or arguments to support candidate design solutions or explain why a specific option ended up as the final solution.

For example, regarding the same flange design example: a functional explanation of the choice of Option 2 would be the following statement:

The design solution (multiple thickness steps) was chosen because for its superior damage control capabilities due to the lower stress concentration unlike Option 1 which has a higher stress concentration.

This kind of explanation is intuitive and useful for the design domain since every artifact is defined for a purpose and this is defined by a set of specific functional requirements. The causal component of the functional explanation is also useful in linking higher level to lower level decisions; thus providing a means to track dependencies throughout the design process. For, example, consider the conceptual-preliminary-detailed design phases described earlier in this chapter. Components and solution elements that are selected at the conceptual design phase create new set of specific requirements for the preliminary phase which in turn also creates specific requirements for the detailed design phases. 'Solutions' which satisfy the specified requirements are selected at each phase until a final solution is determined at the most detailed level. This breakdown of solutions along the lines of functional requirements is one important way of explaining why a particular design solution was realized. Limitations of the functional explanation arise when two or more options provide similar functions and one is chosen over the other. A key question is whether or not a functional explanation will by itself provide satisfactory explanation for the design solution in such a scenario.

2.5.3 Pragmatic Explanation of Design

Key to pragmatic explanations are the concepts of relevance and contrast classes. Within the design domain, a design solution is the end result of the decision-making and this solution together with all other design alternatives constitute the contrast class. By comparing the selected solution to the other alternatives against some specific criteria, it can be explained why that particular design solution was chosen. The criteria are derived from relevance relations aspect of a pragmatic explanation. It refers to the 'events leading up to' the decision point where the design solution was specified. Within aerospace design, relevant events that precede the design decision include the design goal, the requirements, the design problem and the arguments for each design alternative. All these elements act as decision inputs and consequently influence the decision-making process. Note that the relevance relations include the initial conditions (requirements and goals) which are also useful in generating DN explanations.

Again looking at the flange example from section 2.3, Option 1 (one thickness step) and Option 2 (multiple thickness steps) constitute the contrast class for a pragmatic explanation. The relevance relations describe the initial requirements in this case to design a damage-tolerant flange. By analyzing the option 1 and 2 in relation to the requirements, option 2 is chosen as ideal. It also becomes clear from this example that pragmatic explanations could be based on DN or functional explanations in support or objection to options against the requirements or other relevance relations.

2.5.4 Rationale Choice Explanation of Design

The design process, as described earlier (see section 2.2) is an iterative decision-making process which means choices are made right from the start until the final design solution is defined. Essentially, for each stage choices are made about which options to consider and which of the options to focus on as a design choice. Such decisions or choices are not random or made by accident but are only made as deliberate actions to move closer to the design goal (criteria). By the rational choice theory, a specific design solution can be explained by pointing to the fact that it was the best option to satisfy the requirements from a set of other alternatives. Evidently, this means that the rational choice was influenced by some other arguments which provided support for the particular selected option. These arguments are provided by applying the various aforementioned explanation types. It is evident from the previous discussions that although each of the explanation type can provide an argument to support some design choice, they each cover some aspect of the decision, and two or all of them can be combined to present a comprehensive overview of design explanation.

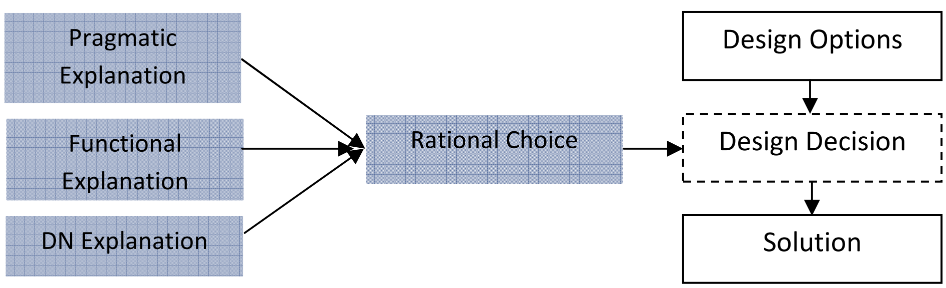


Figure 2-9: Rational choice in design (design decision is a deliberate action)

Ultimately, design solution is the result of a rationale choice on the basis of a criteria applied to potential solutions which satisfactorily meet the specified requirements. To explain the solution implies to understand why the rationale choice was made.

2.6 Conclusion

Four major accounts of explanation have been reviewed and applied to the aerospace design context, thereby identifying elements and concepts within the design domain which are capable of yielding satisfactory explanations for design solutions. Figure 2-10 represents an overview of the various explanation types that have been discussed in this chapter and their corresponding aspects or elements within the design domain that relate to the content requirements for a design rationale capture method.

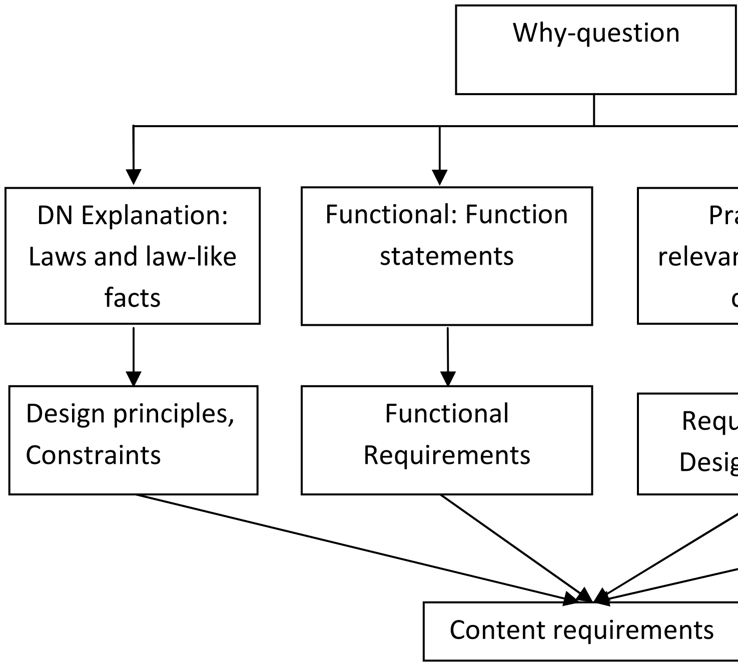


Figure 2-10: Content requirements for explaining a design solution

Together, these elements constitute the content that must be captured by a design rationale method which is aimed at improving the explanation design solutions. Figure 2-11 depicts what we call a design explanation model. This model is an extended (and reorganized) version of the basic explanation model shown in Figure 2-8, and is based on all the elements identified above as content requirements for satisfactory explanation of design solutions. Note that design constraints or principles are not explicitly represented in the model since they are usually translated into requirements as already stated. *Also Why-not* questions can be regarded as a special class of *why* questions. That is, asking why some option was *not* selected as a design solution is equivalent to asking why some other option was selected. For this reason why-not is not included in the design explanation model.

Also embedded in the model is the rationale choice component, showing all the inputs that influence the decision which finally results in a design solution. The relationships between the explanation types and *Arguments* are not modeled for the sake of clarity in addition to the fact that they do not add anything new to the model. As indicated, the motivational factors that influence the rationale choice are the ultimate reasons for the design solution. This decision is influenced by several inputs such as some specific criteria which reflects the most critical requirements and goals that must be achieved by the design solution, the various design options (candidate solutions), and the arguments pros and cons for the design options. The three types of explanation - pragmatic, functional and DN - describe the arguments pointing to the viability of each design option (that is they explain why they are solution candidates in the first place).

The rational choice is then merely an evaluation of these arguments or explanations against the criteria.

Also implicit in the arrows in the figure are causal relations that explain the significance of the elements at the strategic layer on the final solution outcome. For example, the main goal that is to be achieved by some client *causes* requirements (or we have requirements because of the goal) and this in turn *causes* a design problem, and so on; or generally that choices at the solution layer are caused by choices within the decision layer which are also caused by choices made at the highest need layer. The figure is therefore illustrative of the factors that influence decision-making within the design process. All these factors play a part in helping to explain why we arrived at the final solution as the outcome of the design process.

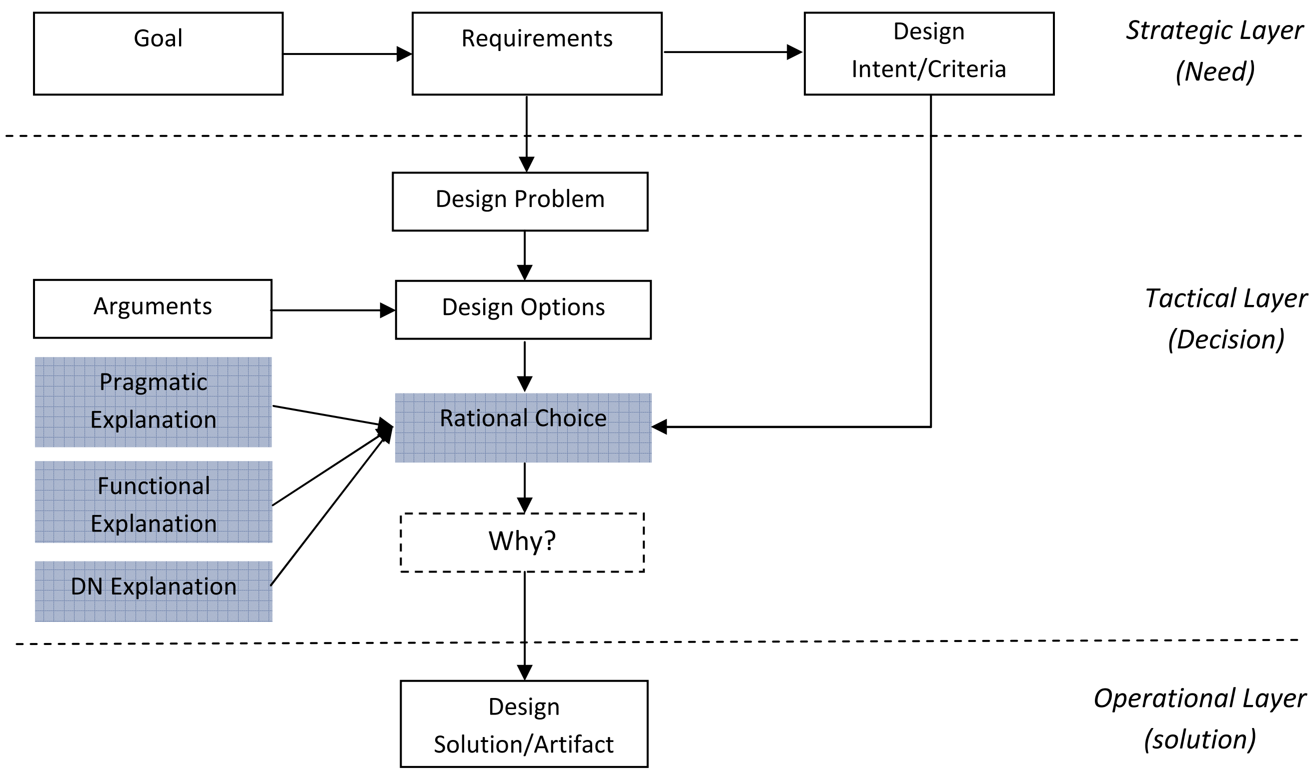


Figure 2-11: Design Explanation Model

Having developed this model of design explanation, the next chapter presents an overview of existing design rationale capture approaches that ends with an assessment of the various methods against the content requirements for design explanation that have been defined here.

3 Approaches to capturing Design Rationale

There is occasions and causes why, and wherefore in all things.

- William Shakespeare

This is the second (and final) chapter that lays out the theoretical background of the thesis. It presents the results of a systematic literature review (SLR) on the subject of design rationale. A systematic review is a method that enables the evaluation and interpretation of all accessible research that is relevant to a research question, subject matter, or event of interest (Kitchenham, 2004). Further, Webster and Watson (2002) defined an effective literature review as one that "…creates a firm foundation for advancing knowledge. It facilitates theory development, closes areas where a plethora of research exists, and uncovers areas where research is needed." Thus, a review of prior, relevant literature is an essential feature of any academic project. There are numerous motivations for carrying out an SLR. Specifically for this research, the SLR is aimed at establishing the 'state of the field' of design rationale research, especially in areas which are relevant to the thesis topic.

In particular, the review is aimed at addressing the following questions/topics:

- *What is design rationale?*
- *What DR approaches are there?*
- *What do the methods aim to capture, and how are they captured and represented?*

3.1 What is Design Rationale?

Design rationale is a topic which implies different things to different people. To some it implies argumentation and frameworks for argumentation. To others it implies the documentation of design, like that required for many types of industrial or government work. Still others describe design rationale as the capture and potential reuse of normal communication about design. This is to be expected since the word design itself has different connotations as mentioned in the previous chapter.

The concept of design rationale which dates back to the work of Rittel and Webber (1979) has been thoroughly investigated in the literature from various perspectives and academic disciplines. This means that design rationale has a broad sense of meaning with several different definitions or notions as to what exactly can be considered as rationale. Design rationale can be defined as the explicit documentation of the reasoning behind the design choices in a design solution, the justification for it, the other alternatives or options considered, the tradeoffs evaluated, and the argumentation that led to the decision.

Table 3-1: Different perspectives of Design Rationale

No	Author	Meaning of design rationale
1	Klein(1993)	The underlying intent and logical support for the decisions made during the design of an artifact.
2	Chandrasekaran et al. (1993)	A record of design activity: of alternatives available, choices made the reasons for them, and explanations of how a proposed design is intended to work.
3	MacLean et al. (1996)	A representation for explicitly documenting the reasoning and argumentation that makes sense of a specific artifact.
4	Lee (1997)	The reasons behind a design decision, the justification for it, the other alternatives considered, the tradeoffs evaluated, and the argument that led to the decision.
5	Regli et al. (2000)	An explanation of why an artifact or some part of it has been designed in a particular way.
6	Burge and Brown (2000)	The decisions taken during the design analysis phase and the reasons that lead to such decisions

The various definitions portray the different perspectives on the subject; however the basic idea seems to be generally similar. Design rationale relates to information on the intent and reasons behind a design decision, as well as the justification for it, the other alternatives that were considered but eventually discarded, the criteria for alternative selection and the arguments that led to the decision. Furthermore, this information can be used to answer a question why an , or some feature of it, has been designed in a specific way. This is the conception of design rationale which is adopted for this thesis.

3.2 Design Rationale Approaches

According to Regli et al. (2000), the main approaches to developing design rationale systems are process-oriented and feature-oriented. In dynamic design domains the process-oriented approach is used to give historical representation of s while in fields with a relatively high degree of standardization, the feature-oriented approach is used to give logical representation of s, to follow the rigorous and logical rules of the design process.

Specifically, process-oriented approaches emphasize the design rationale as a history of the design process. Most design rationale approaches are process-oriented. The representation schema of process-oriented rationale system is generally graph-based using nodes and links, with nodes indicating possible issues and links indicating relationships among the nodes.

Feature-oriented design rationale systems contain domain knowledge-bases, which can be used to support automated reasoning and the generation of design rationale. Representations of design rationale are thus usually more formal than in a process-oriented design rationale system. In some systems, the design rationale is represented with links to the existing knowledge-base.

Aside this high-level classification, there are yet a number of different ways to characterize DR approaches. Key distinguishing features are how the rationale information is captured, how it is represented, and how it can be used.

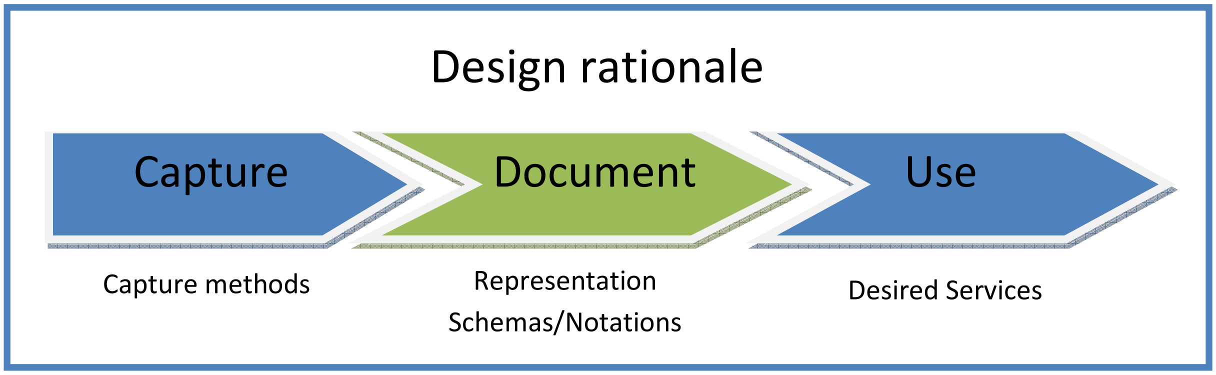


Figure 3-1: Main issues characterizing DR Approaches

3.2.1 Capturing Design Rationale

There are two main methods to capture design rationale: automatic and user-intervention. The automated method does not require the designer to input or record design discussions, decisions and reasoning themselves while the user-intervention method does. These two methods are used to capture design rationale using either process-oriented or feature-oriented approach. In the process-oriented approach design rationale is seen as a history of the design process while in the feature-oriented approach design rationale has a formal, logical structure and is supported by domain knowledge-bases. Thus in fields with relatively high degree of standardization the feature-oriented approach is used while the process-oriented approach is used in dynamic design domains.

Lee (1997) offers the following classification for the rationale capture systems:

- Reconstruction: Captured outside the design process, usually after it has been performed using information recorded during design.
- Automatic generation: Generated from an execution history (eg. In Myers et al. (2000); Ishino and Jin (2002)

- Methodological by-product: Emerges during the design process. The methodology aids design and captures rationale

- Apprentice: The system or 'apprentice' learns about the features that make a specific case different from the standard. Whenever the designer proposes a design action that differs from the apprentice's expectations, the interface will ask for the designer for justifications to explain the differences (e.g. in Garcia and Howard, 1992;)

- A final method used for design rationale capture is the Historian approach (Chen et al., 1990). In this approach, a person or computer program keeps track of all actions during the design process. This method is similar to apprentice, except the system does not make suggestions. It is also similar to automatic generation except that the rational is specifically recorded during the design process, not generated later.

3.2.2 Representation of Design rationale

Almost any type of decision related information is potentially useful and can be classified as some type of rationale (Burge and Brown, 1998). It is however impossible to capture and represent an entire design rationale explicitly (Lee, 1997). As noted above, design rationale is presented in a broad sense in the literature and can mean almost anything in the design process which can be used to trace a reason of some aspect or feature of the design. What is captured and explicitly represented, thus, depends on the anticipated uses of the rationale information or the services the intended DR system is expected to provide (Lee, 1997), as well as the representation schema that is adopted to record the rationale (Regli et al., 2000).

A review of the various representation schemas (to be presented shortly in section) that have been used as DR notations reveals the different emphasis they place on different aspects of design rationale, and this is reflected in *what* they attempt to capture as rationale. In spite of the differences, Lee (1997) identifies a generic structure to *what* is being represented on the basis of a survey of existing and proposed DR systems. The structure takes the form of layers, and is described below:

Design Intent Layer: Highest level of design rationale which contains meta-information underlying design decisions such as intents, strategies, goals, and requirements.

Design Artifact Layer: Information about the 'thing' being designed (such as components and how they are related).

Decision Layer: This layer characterizes the generic structure of a decision process, regardless of use; and provides detailed information that describes the decisions made during the design process. It consists of five sub-layers which are listed and described below:

Issue: individual issues and their relations (generates, depends-on, replaces)

Argument: The arguments underlying a decision (supports, refutes, qualifies)

Alternative: individual alternatives and their relations (component-of, incompatible, specializes)

Evaluation: evaluations- used to rank alternatives

Criteria: criteria used and their relations (mutually-exclusive, tradeoffs, specializes). Criteria are used to group evaluations and arguments.

3.2.3 Representation Schemas

Again, the details of how design rationales are to be represented depends heavily on the representation schemas, although in general the 'degree of formality' ranges from informal to formal (Moran and Carroll, 1996; Lee, 1997; Regli et al., 2000).

- Informal representations capture rationales in an unstructured form such as descriptions in a natural language, audio/video recordings, and raw drawings or sketches. These notations are easy to create but cannot be easily interpreted by the system, making them ill-suited for most computational purposes.

- Semi-formal representations are the most suitable if the primary services are to help people archive, retrieve and examine the reasons for their decisions. Here, only parts of the representation are computer readable while the rest is informal.

- In a formal representation, objects and relations are defined as formal objects and the system can interpret and manipulate using formal operations.

A design rationale representation explicitly documents the reasoning and argumentation that occurs during design; and it determines the methods used to capture and retrieve the design rationale (Regli et al., 2000). Selecting an appropriate representation schema is thus critical and also depends on the anticipated uses of the rationale that is captured or the services a DR system is expected to provide.

Argumentation-Based Approach

An argumentation-based design rationale uses semi-formal graphical format for laying out the structure of arguments that lead to decisions. It uses a node-and-link representation where nodes represent a component and links represents relationships between those components. The most common argument structures are IBIS, QOC and DRL (Regli et al., 2000; Stumpf, 2004). In addition, Toulmin's model which is described as the earliest argumentation structure is also described.

a) Toulmin Model

The Toulmin argument structures (1958) approach to argumentation is essentially not a design rationale approach but has formed the basis of argumentation-based design rationale approaches. Toulmin developed an alternative to theories of formal logic that attempts to provide a more practice-based approach to the analysis of problem structures. His approach involves the production of argument structures that are represented graphically as shown in the example in Figure 3-2 below:

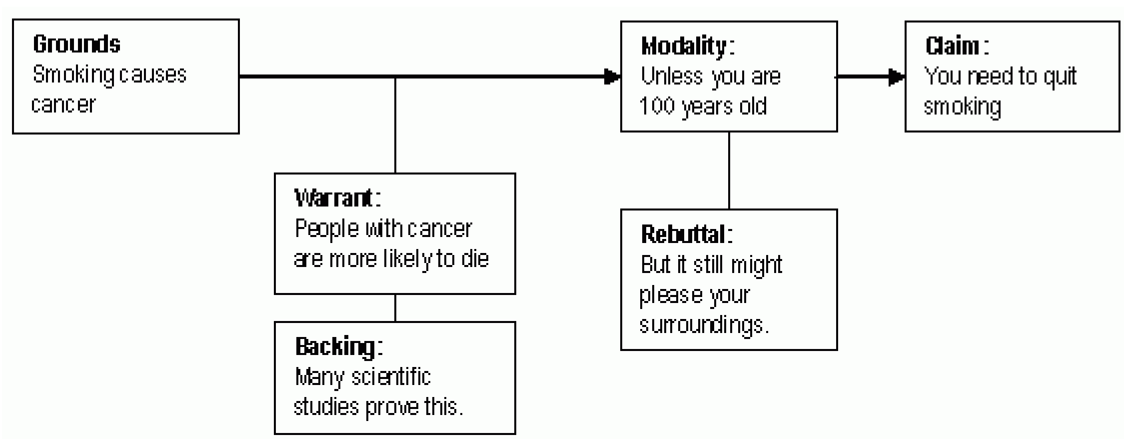


Figure 3-2: Toulmin Argument Structures (Toulmin, 1958)

The Toulmin argument structures have six components:

- Claim – this is the expressed opinion or conclusion that the arguer wants accepted by the audience;
- Grounds – this is the evidence or data for the arguer's claim
- Warrant – this is the arguer's reasoning for connecting the data to the claim
- Backing – Further facts or reasoning used to support or legitimate the warrant
- Rebuttal – this represents circumstances or conditions that undermine the argument;
- Qualifier – an adverbial phrase indicating the strength of the claim (such as certainly, probably etc).

(b) IBIS

Several authors (e.g. Moran and Carroll, 1996; Bracewell et al., 2009) point to Issues-based Information Systems (IBIS) introduced by Kunz & Rittel (1970) as the earliest proposed method for capturing design rationale. IBIS was created to help deal with what they authors referred to as 'wicked problems' of architectural design and city planning, problems that consisted of hundreds or thousands of different issues and that involved large teams of stakeholders attempting to develop solutions. The IBIS model takes an argumentation view of the planning and design process and identifies three key elements that make up a given debate. Elements of a problem domain are represented by three node types: issues are identified for which stakeholders take positions; these positions are backed by arguments (See Figure 3-3).

In addition to these three central IBIS objects, the model includes eight different link types that may be used to express the relationships between objects. These include generalizes, specializes, replaces, questions, is-suggested-by, responds-to, supports, and objects-to.

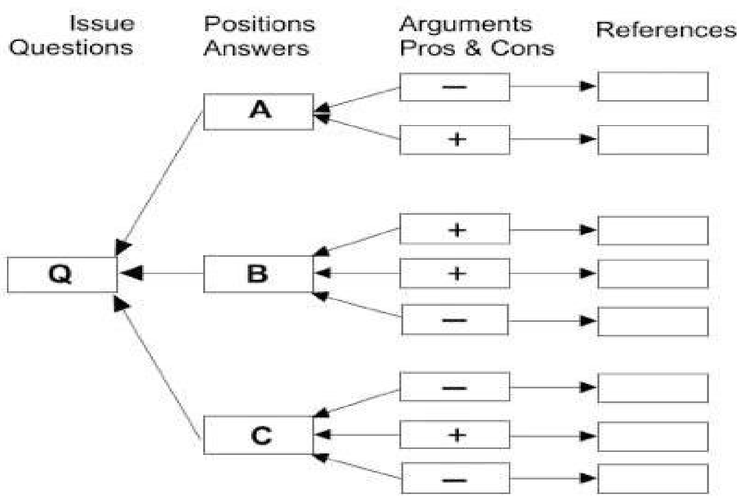


Figure 3-3: The Issue Based Information System (IBIS)

(c) QOC

The semi-formal notation QOC for Questions, Options, Criteria, is part of the Design Space Analysis (DSA) approach developed by MacLean and others at Rank Xerox EuroPARC (MacLean, et al, 1996; MacLean & McKerlie, 1995). DSA is concerned with looking beyond artifact produced by the design process to the broader issues that resulted in its development, which is called the design space. A DSA is a separate deliverable meant to be produced alongside the designed artifact and other supporting specifications and documentation.

According to the authors, DSA/QOC contributes to the design process by exposing assumptions being made by designers, raising new questions, challenging the legitimacy of the design criteria, and showing how newly identified options might overcome problems with those previously identified. This DSA/QOC notation allows designers to capture not only elements of the final design, but also the reasons why a final design turned out the way it did, what alternatives were available, and why a particular one was chosen (MacLean et al, 1996).

In the QOC notation, questions highlight issues that have been identified as relevant to the design, options are the potential solution approaches that have been identified to address a given question, and criteria are the reasons that are considered for or against each of the identified options. Whether a criterion is considered a positive or negative factor in the evaluation of a given option is represented in the links, known as assessments, between options and criteria. Supporting criteria are linked to options using a solid line; Criteria that weigh against a given option are linked using a dashed or dotted line. One important note is that assessments in QOC are not assigned weights to represent their relative importance to the argument for an option. Figure 3-4 below presents a simple QOC example showing an assessment of a design question related to the currency-handling model of a business software application.

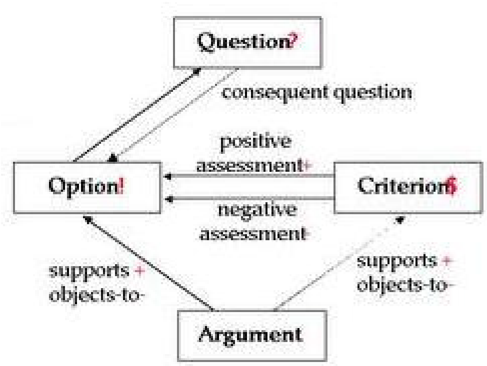


Figure 3-4: QOC Approach

Functional Representation (FR)

Functional representation (Chandrasekaran et al., 1993) is a modified form of argumentation-based representation. This method is a representational scheme for the causal processes that culminate in the achievement of device functions and uses design rationale as an account of how the designed artifact serves or satisfies expected functionality. It takes a top-down approach to represent a device; that is, the overall function is described first and the behaviour of each component is described in the context of this function (Regli et al., 2000). As design rationale, FR is able to support control of distributed design activity; reassessment of device functions; generation of diagnostic knowledge; simulation and design verification; redesign; and case-based design. FR provides only a partial rationale for choices made about components and their configuration. Thus, its limitation is that FR only captures the causal knowledge about device operation, unable to trace some other aspects of rationale such as design options considered and arguments for these options. Figure 3-5 shows a sample FR representation, indicating how purpose, function, behaviour and structure are generally decomposed down to sub-functions, sub-behaviours and sub-structures.

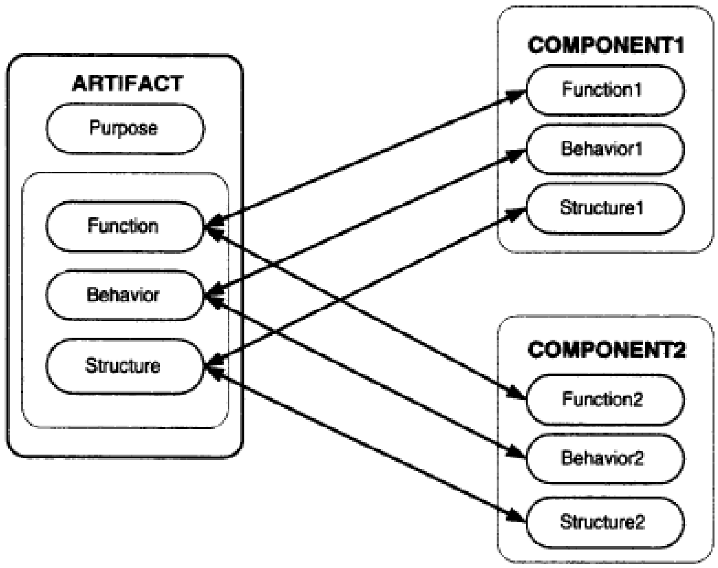


Figure 3-5: Whole-component decomposition as a functional representation (Regli et al., 2000)

Active Design Documentation (ADD)

This technique represents design rationale by documenting the complete design decision path associated with the artifact as well as the rationale behind each decision presented by the user. Other versions of the model use the same basic model as ADD but store the wealth of knowledge by organizing it into high-level rhetorical structures (Garcia et al, 1997).

ADD is an integrated computational model for assisting designers in documenting projects at design time and represents design rationale as a combination of argumentation-based and model-based rationale. It works by documenting the complete design decision path associated with the , as well as the rationale behind each decision presented by the user. This solution path represents the designers' strategy, in which each node is a sequentially linked decision. Users can explore the design rationale in several ways: through the history tree, the dependency tree, annotations, and (most importantly) by asking direct questions. One limitation of the ADD is that the system only provides a one-paragraph answer, without references to the relevant data in the knowledge base (Regeli et al., 2000).

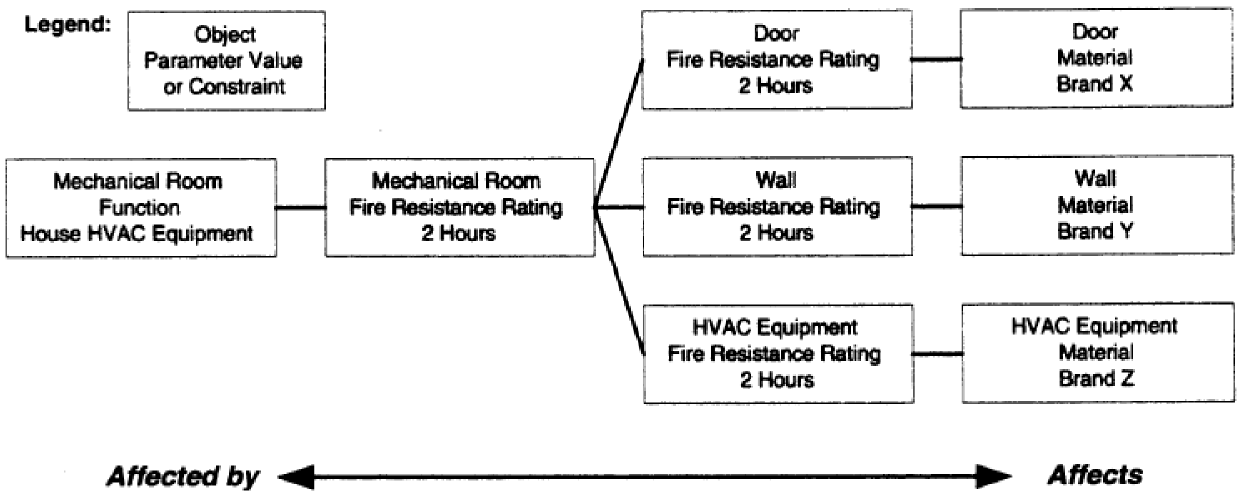


Figure 3-6: A parameter dependency network example for ADD (de la Garza & Alcantara, 1997)

Descriptive or Free Text Approach

This method records the history of design activities, work flow and the communication between designers in a raw, unstructured form (Reeves and Shipman 1992; Conklin and Yakemovic K. C., 1991; Shipman and McCall, 1997). This approach defines no specific rationale capture method and is not used in further analysis in this thesis.

3.2.4 What are the success criteria for DR systems?

Criteria for success of DR systems reflect the general perception of technology acceptance, notably the technology acceptance model (Davies, 1989) which attributes the adoption of a technological system to its perceived usefulness and ease-of-use. Specifically, a key criterion which is repeatedly mentioned in the literature is the fact that a DR system must be able to capture the intended rationale with as little disruption of the normal process (Conklin and Yakemovic, 1991) or hinder the daily work of designers (Bracewell, 2009).

The adoption of a DR representation schema or notation also follows along these lines as indicated by Lee and Lai (1996). A DR representation schema should be capable of expressing domain knowledge while at the same time being amenable to human and computer manipulation.

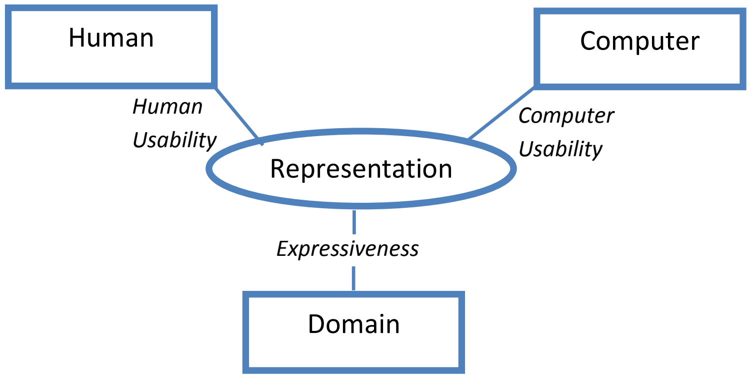


Figure 3-7: Elements in computer-supported activities (Lee and Lai, 1996)

The expressiveness of a representation describes its coverage of the target domain to be represented: is the vocabulary sufficient to represent all of the important concepts, relationships, and scenarios of use? Moreover, even if certain classes of information are logically representable, the extent to which the representation eases access (visually, or computationally) to important information, and hides irrelevant detail, is clearly important for an interactive design representation (Buckinham Shum, 1996). In this thesis the success criteria for a design rationale representation schema include being based on conceptual soundness which proves that the schema is expressive enough to capture and represent enough content to explain design solutions (that is complete and relevant content). Another success criterion is to be able to provide complete and satisfactory explanations for design solutions.

3.3 Conclusion

The overview of DR approaches indicates the different conceptions of design rationale and the element that are intended to be captured. However, it is also clear that what is captured depends heavily on the goal of the rationale capture method: what do we want to do with design rationale? As stated in the introductory chapter, the goal for capturing design rationale in this thesis is to improve the explanation of design solutions. That is helping answer the why-question: *why the design solution does looks the way it is?* Recall the design explanation model from the concluding section of the last chapter (slightly modified version shown in below). Since design rationale represents the content to answer the why-question, we introduce design rationale in place of the 'why' component. That is to say that, design rationale stems mainly from a rationale choice decision that is made to arrive at a design solution. This decision is influenced by several inputs such as some specific criteria which reflects the most critical requirements and goals that must be achieved by the design solution, the various design options (candidate solutions), and the arguments pros and cons for the design options. Design rationale, then, refers to the rational choice decision along with its inputs which justifies the design solution given the initial requirements and some specific criteria.

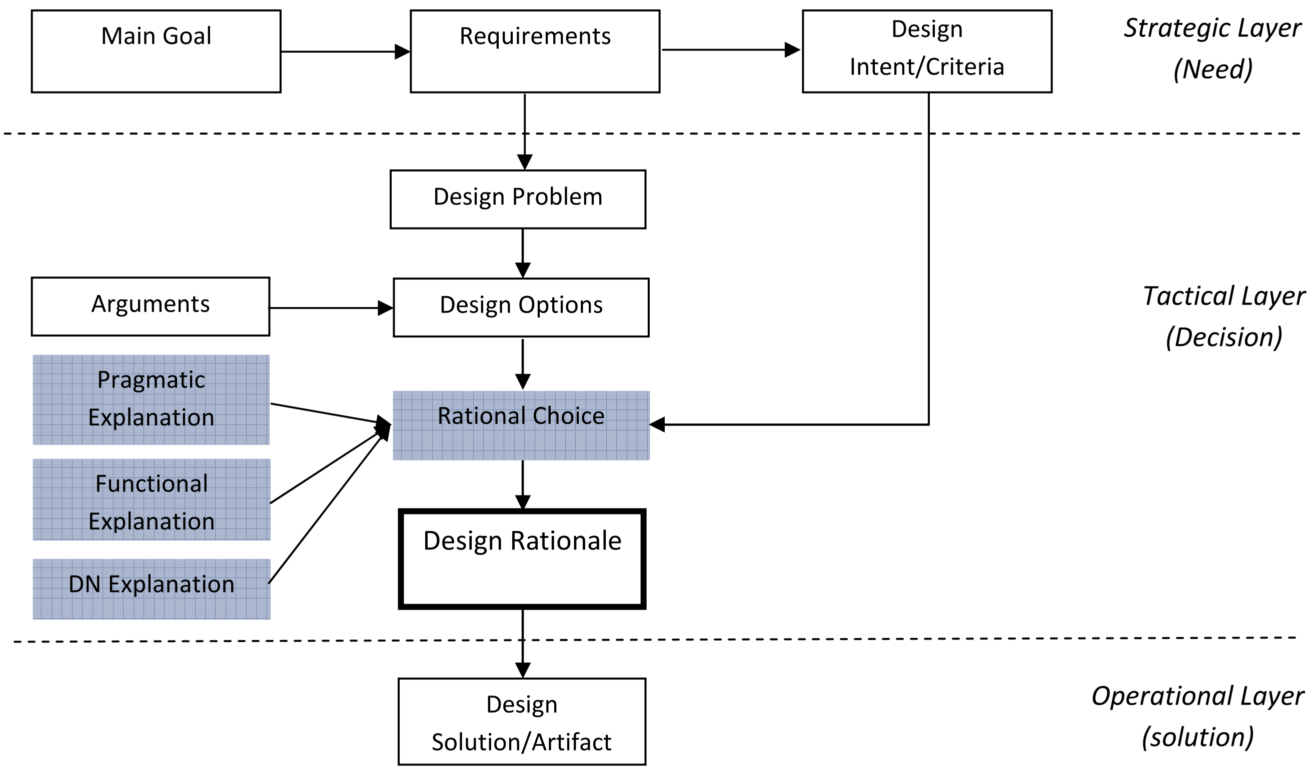


Figure 3-8: Design rationale as explanation for design solutions

The ADD approach, being an extension of argumentation approaches such as IBIS and QOC, is also adequate at capturing decision layer elements such as arguments, covering laws and law-like facts, and design options. But like QOC and IBIS, it also lacks explicit linkages with contextual elements such as design goal, requirements and criteria. The added advantage of the ADD though, is its tracking of dependency links between decisions. Table 3-3 present an overview of the design rationale representation schemas discussed in this chapter and an evaluation of the schemas against the explanation types and content requirements from the last chapter respectively. Clearly, it can be observed in Table 3-2 that the existing schemas are largely semi-formal and mostly elements within the decision layer (Lee, 1997) or tactical layer of design choices. Using the content shown in Table 3-2 for all rationale capture methods as basis, each of them is evaluated against the derived content from the four explanation types and summarized in Table 3-3. A discussion of the evaluations follows shortly. Note that a tick(√) in the table against some content means explicit capture of that content while a plus (+) indicates that the content is captured to some extent in one way or another.

Table 3-2: Overview of rationale representation schemas

Schema	Content	Rationale Layer (Lee, 1997)	Representation Structure
Toulmin	Argument structures:	Decision Layer	Semi-formal
IBIS	Issues, Positions, Arguments	Decision Layer	Semi-formal
QOC	Design Space – Questions, Options, Criteria	Decision Layer	Semi-formal
Functional	Causal role of a component in relation to a function	Design Layer Decision layer	Informal/semi-formal
ADD	Elements of decision-making: design alternatives, the evaluation space and criteria, and the argument structure	Design Layer Decision Layer	Semi-formal

Table 3-3: Evaluation of representation schemas against content requirements for explanation

Explanation Type	Required Content	Toulmin	IBIS	QOC	Functional	ADD
Rational Choice Explanation	Design Goal				√	
	Criteria			√		
	Arguments	√	√	√	√	√
DN Explanation	Laws/Law like statements	√	√	√	√	√
Functional Explanation	Functional Requirements	+	+	+	√	+
Pragmatic Explanation	Requirements	+	+	+	+	+
	Design Options	+	√	√	√	√

The Toulmin model is essentially an argumentation structure, expressively representing claims and the argument to support the claims or refute, both of which can in turn be backed by some piece of evidence. Hence this model can capture *arguments* in detailed form. These arguments can make use of *laws of law-like facts* and arguably can represent *design options* if one structure is used to represent the argumentation behind each option. The downside of this model is that options are not linked to a single *design goal* or problem. Hence options can only be evaluated with respect to the arguments but with no room to capture the context. Also, *requirements (also functional requirements)* are not explicitly linked to decision-making although it can be said that such requirements can be found in the arguments. Overall, the Toulmin model can capture some content for explanation but is not completely adequate especially with respect to design.

In many ways, IBIS and QOC are similar: the both capture *design problems* as issues and questions; and design *options as positions and options respectively.* The main difference between the two lie in the fact that IBIS attempts to capture *arguments* pros and cons for each position (design option) but QOC goes the extra step to represent evaluations of the options not only on the basis of the indicated arguments but provide a means of capturing *criteria* that are used to positively or negatively assess the options in the light of the presented arguments. Both methods are however both lacking when it comes to representing contextual information higher than design problem such as requirements and design goals (although QOC captures design criteria which is also a contextual element). QOC is therefore a bit more expressive compared to IBIS with respect to capturing design explanation content (and both are better than the Toulmin model), but it is also not adequate if a full cover of design explanation content is required.

The ADD approach, being an extension of argumentation approaches such as IBIS and QOC, is also adequate at capturing decision layer elements such as arguments, covering laws and law-like facts, and design options. But like QOC and IBIS, it also lacks explicit linkages with contextual elements such as design goal, requirements and criteria. The added advantage of the ADD though, is its tracking of dependency links between decisions. The functional approach is very adequate in capturing functional requirements and to some extent all other requirements can also be translated into *functional requirements*. Function statements can be seen as *arguments* and these could rely on certain *laws/law-like facts*; and different function statements for the same problem represent *design options*. *Design goal* is captured as the purpose of the to be designed. Again, the problem here is the explicit representation of *criteria* to select a single option where there is more than one possible design solution (which is most often the case in a design situation).

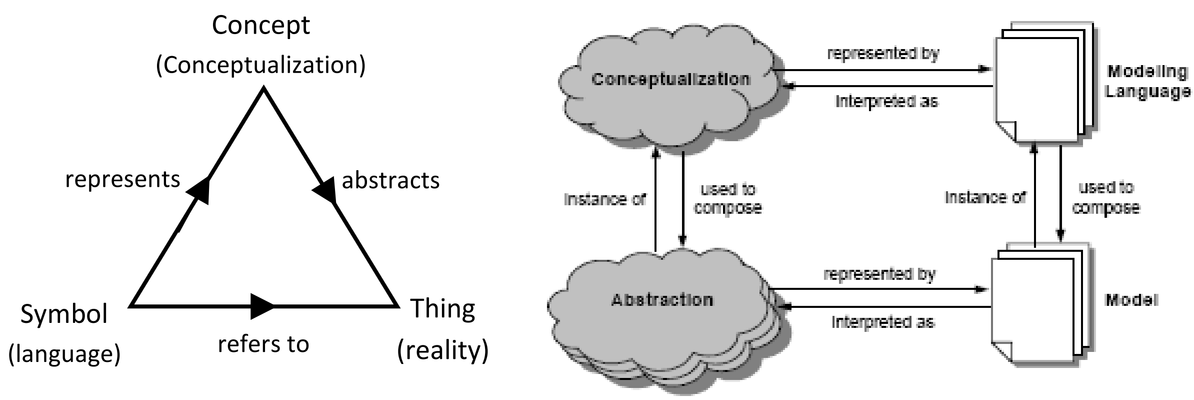
In conclusion, almost all the schemas focus on capturing decision elements but largely ignore capturing or linking those decisions to elements within the design intent (or what we call the strategic layer) which define the context for the decision-making and have been shown to help account for the explanation of design solutions. In the light of these inadequacies of current design rationale schemas, a proposed rationale-based ontology (RaDEX) is defined and developed to satisfy rationale requirements for explaining design solutions. Chapter 4 describes and implements an ontology-based approach to capturing design rationale.

4 An ontology-based Approach

The last two chapters have defined the requirement with respect to content for an ideal design rationale method which has the main goal of improving explanation of design solutions. This chapter describes a methodological framework and follows it to develop an ontology that is proposed as an ideal solution. Section 4.1 gives a short introduction about the ontology after which sections 4.2 discusses the idea of an ontology-based approach for rationale capture. Next, Section 4.3 introduces the RaDEX ontology; and finally section 4.4 walks through a methodology to design and implement the RaDEX ontology.

4.1 Ontologies

Within the knowledge engineering community, the word 'ontology' has gained considerable attention although its exact meaning is not always clear, and can refer to several different things (Guarino & Giaretta, 1995; Guizzardi, 2007). The term is borrowed from philosophy, where an Ontology is described as a systematic account of existence (Fensel, 2001). In the context of this thesis, however, we refer to ontology as an explicit specification of a contextualization Gruber (1993). The specification defines a set of representational primitives with which to model a domain of knowledge or discourse. These representational primitives are typically classes (or sets), attributes (or properties), and relationships or relations among class members (Gruber, 2009). The idea of a conceptualization is regarded as a semantic structure which encodes the implicit rules constraining the structure of a piece of reality: a conceptualization is an abstract, simplified view of the world that we wish to represent for a specific purpose (Guarino & Giaretta, 1995). See Figure 4-1 for a representation of the relationships between the various concepts.



(a) **(b)**

Figure 4-1: Conceptualization, Abstraction, Modeling Language and Model (Guizzardi, 2007)

Picture (b) in Figure 4-1 is an elaboration of the relationships depicted in (a). Ontology representation languages (L) can be seen as a modelling language that is used to specify some concept which is based on some aspect of the real world (domain) or make it explicit; resulting in some model (M). M then, is an ontology which reflects the domain that was modeled and can be used to for several purposes. These include (Noy and McGuinness, 2001):

- To share common understanding of the structure of information among people or software agents
- To enable reuse of domain knowledge
- To make domain assumptions explicit
- To separate domain knowledge from the operational knowledge
- To analyze domain knowledge

Once created, ontologies can be used to define the structure of databases or knowledge-bases for use in a complete knowledge-based system or applied directly in software agents, problem-solving methods and domain-independent applications as models that describe the problem domain (see Figure 4-2).

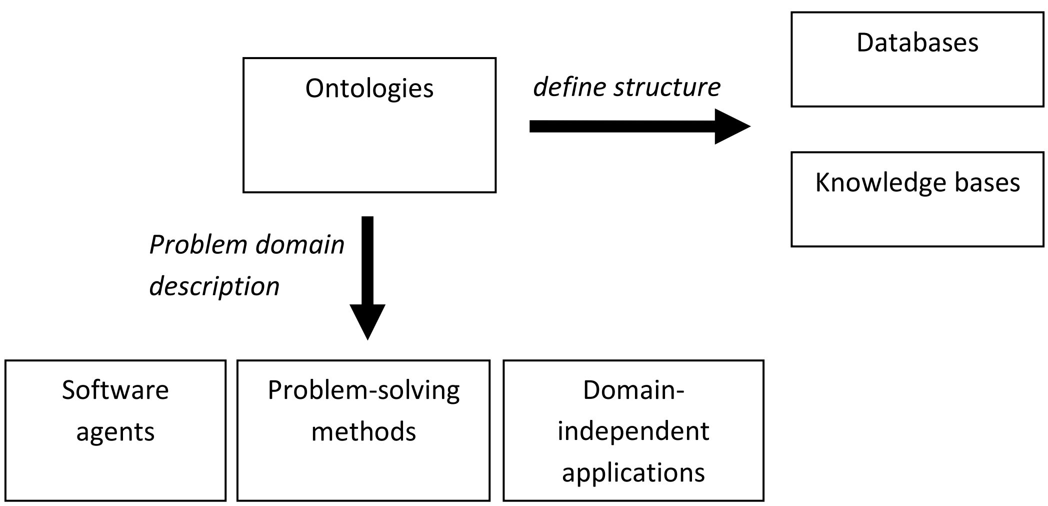


Figure 4-2: Using ontologies in practice

4.2 Ontology as Design Rationale Representation Schema

A key question that motivates this section is whether ontologies are good enough for representing design rationale. The discussion above illustrates the importance of ontologies as languages for representing languages. According to Fensel (2001, p3), ontologies were developed in Artificial Intelligence mainly for the purpose of facilitating knowledge sharing and reuse. More specifically, an ontology can be viewed as the skeletal framework for a knowledge-based system: It lays out the concepts, terminology, and structure which are to be used to organize specific knowledge in the knowledge base (Mayer et al., 1992). Since design rationale is essentially knowledge (see chapter 3), what makes ontologies good candidates for representing design rationale is the fact that they can be used as a notation to represent knowledge in a formally precise and computable way (de Medeiros et al., 2005); whiles at the same time presenting the captured knowledge in a human-readable form (Gruber, 2009). Ontologies, thus, present the same advantages of semi-formal representation schemas that provide some computation power but still understandable by the human who is the key source of the knowledge that is to be represented. For example, concept maps (Novak, 1998) can be used to provide a human-centered interface to display the structure, content, and scope of an ontology.

Furthermore, inference over design rationale can lead to the discovery of previously undocumented rationale or assumptions. Since an ontology is essentially a vocabulary of a domain, a key requirement for design rationale ontology is its expressive power. That is, the extent to which its vocabulary can represent the content we seek to capture. The content requirements have already been defined and so we expect that by following a systematic approach design and implement the ontology, it will be

4.3 The RaDEX ontology

The RaDEX ontology described in this section is viewed as a conceptual foundation of a knowledge-base for a design rational capture tool. The purpose of the ontology is to transfer captured design rationale (knowledge) into a knowledge base system by transforming and representing the acquired knowledge using suitable knowledge representation formalisms. The ontology is expressed as a representation language constituted by its syntax and a specific vocabulary that is used to describe a certain reality (in the context of this thesis, design rationale), plus a set of explicit assumptions regarding the intended meaning (semantics) of the vocabulary words (Guarino, 1995). The vocabulary of the ontology is critical since one of the main success factors behind the use of a modeling language lies in the language's ability to provide its intended users a set of modeling primitives that can directly express relevant domain concepts.

In this respect, the RaDEX ontology describes a set of primitives or elements (classes, properties, relations and constraints) that express the design rationale domain. The RaDEX ontology adopts elements of existing some existing rationale methods (such as the QOC and Toulmin model) and complements them with additional concepts (such as requirements, design goals, mandate etc) to enhance the expressiveness of the ontology with respect to the adequately representing the domain under consideration, that is explanation-capable design rationale. Representation of the context is important since knowledge is created in context and such contextual information is crucial for reuse scenarios. The ontology serves an underlying argumentation model which can be further exploited to create a DR capture system.

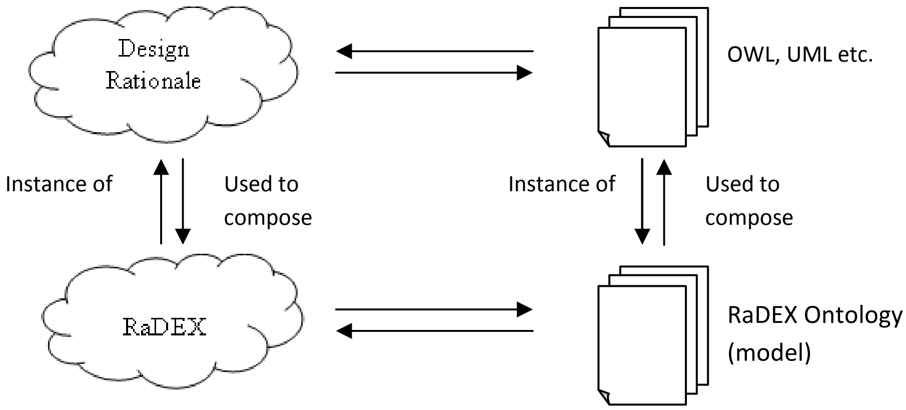


Figure 4-3: Application of Guizzardi's (2007) model to this thesis

4.4 Design and Construction of the RaDEX Ontology

In his paper, Gruber (1995) asserts that ontologies are designed. This is on the basis that choosing how to represent something in an ontology constitute design decisions. Like any design task, this calls for the need of objective method and criteria that are founded on the purpose of the resulting specification to guide the design and evaluation of ontologies (Gruber, 1995; Uschold & Grüninger, 1996). In developing, an ontology, several basic questions arise related to the methodologies, tools and languages to be used in its development process: To systematically build an ontology, an important task is to adopt a methodology that clearly describes the life-cycle of the ontology building process, and points out the specific activities to be carried out at each stage.

Many methodologies have been proposed or used to develop ontologies that have been reported in the literature: (scheduling, control, quality assurance, specification, knowledge acquisition, conceptualization, integration, formalization, implementation, evaluation, maintenance, documentation and configuration management (Corcho et al., 2003). However, the focus here is mainly on a methodology for the design and implementation of the ontology. Issues such as ontology maintenance and integration are not addressed in this thesis. Three fundamental rules in ontology design are adopted as a starting point (Noy & McGuinness, 2001):

1. *There is no one correct way to model a domain – there are always viable alternatives. The best solution almost always depends on the application that you have in mind and the extensions that you anticipate.*
2. *Ontology development is necessarily an iterative process.*
3. *Concepts in the ontology should be close to objects (physical or logical) and relationships in your domain of interest.*

Thus the main modeling decisions involved in ontology design are guided by the purpose and goal of the ontology. With this in mind, a simple ontology design methodology is created by combining Noy and McGuiness' (2001) "Simple knowledge-engineering methodology" and METHONTOLOGY (Fernandez-Lopez, 1999). This methodology is shown in Figure 4-4, and subsequently described.

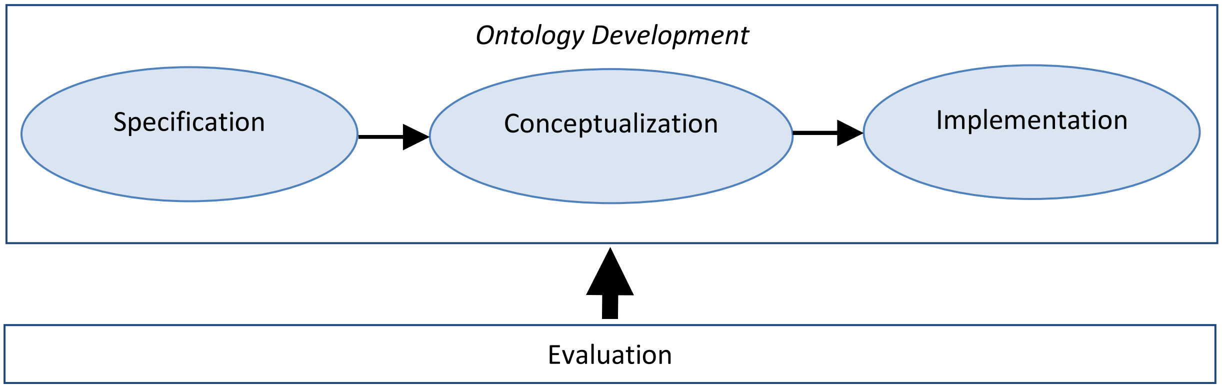


Figure 4-4: An ontology engineering methodology

4.4.1 Specification

The objective of this phase is to produce an initial informal, semi-formal or formal specification of the ontology using a set of intermediate representations of the ontology (Fernandez et al., 1999) or defining relevant competency questions (Gruninger and Fox, 1995; Fernandez et al., 1999). Activities within this phase include determining the domain or purpose of the ontology as well as delimiting its scope.

The aim of the specification phase is to determine the purpose and scope of the ontology, thus explicitly defining the requirements for its construction.

Domain and Purpose

Representation of design rationale is the domain of the RaDEX ontology. This ontology could serve as a skeletal foundation for a knowledge-based tool to capture design rationale in engineering design practice. The ontology defines the critical elements or concepts that are to be captured as rationale and link these concepts using relationships that reflect the domain. Ultimately, the knowledge (design rationale) that is captured according to the ontology is to help improve the explanation of design solutions.

Scope

Defining the scope of the ontology is critical since it impacts the content that the ontology can capture and represent. As described in the previous chapter, the scope of the ontology can be defined by intermediate specifications or by a set of competency questions that a knowledge base based on the ontology should answer. Although it shouldn't be an exhaustive list, a set of competency questions must relate to explanation of a design solution and it is difficult to come up with a representative set. We therefore chose to create an intermediate specification using the content requirements for explaining design solution developed in chapter 2.

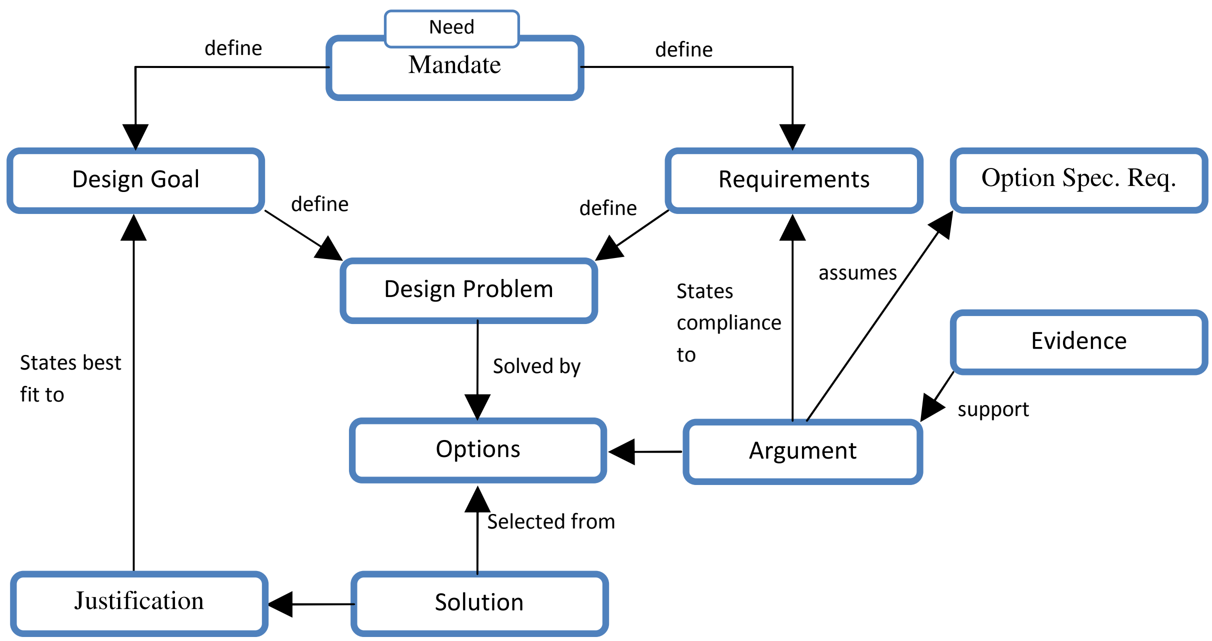


Figure 4-5: An informal specification of the RaDEX ontological schema

4.4.2 Conceptualization

This phase aims at structuring the domain knowledge using a conceptual domain that describes the problem and its solution in terms of the domain vocabulary identified in the specification stage. The main activity here is to enumerate the key terms, including concepts, instances, verbs and properties.

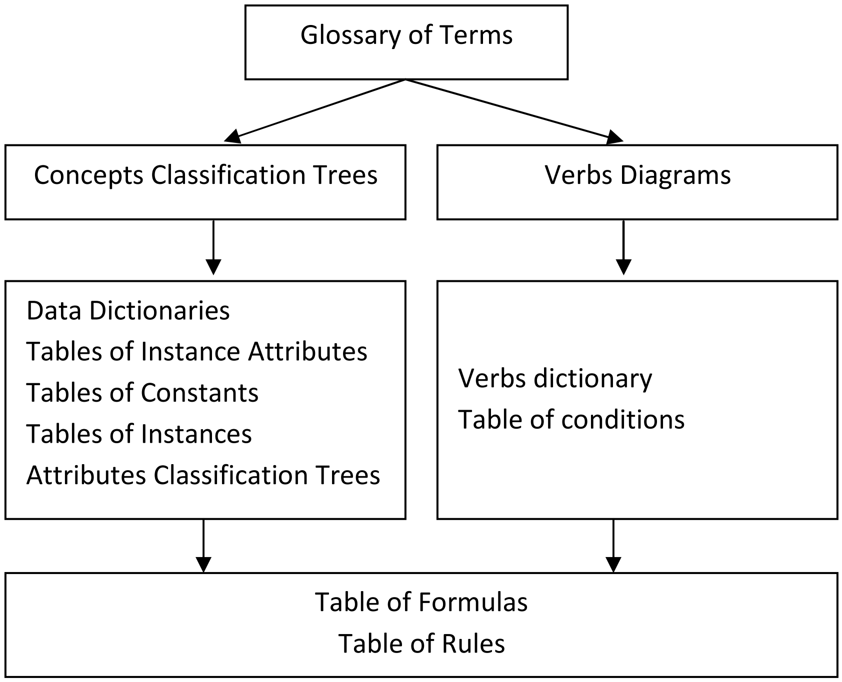


Figure 4-6: Conceptualization phase of ontology development

Important Terms

Important terms are mostly defined in the specification phase above and derived from the content requirements from chapter 2. A full list of the identified key terms can be found in Table 4-1.

Table 4-1: Glossary of terms for the RaDEX ontology

Mandate	Options	Constraints	Criteria	complements	Backed-by
Requirements	Argument	Design principles	Defines	Solved-by	Refuted-by
Option specific requirements	Evidence	Functional requirements	Creates	Supported-by	
Design problem	Design Solution	Design goal	introduces	Challenged-by	

Define Classses, Properties, Constraints and Instances

There are several possible approaches in developing a class hierarchy (Uschold and Gruninger, 1996):

- A top-down development process starts with the definition of the most general concepts in the domain and subsequent specialization of the concepts.
- A bottom-up development process starts with the definition of the most specific classes, the leaves of the hierarchy, with subsequent grouping of these classes into more general concepts.
- A combination development process is a combination of the top-down and bottom-up approaches: We define the more salient concepts first, and then generalize and specialize them appropriately.

The third approach, a combination of the top-down and bottom-up approaches sound intuitively ideal for defining the class hierarchy, and is used in the analysis. One main advantage is that allows for the identification of the primary concepts of the ontology after which the general terms can be specialized or generalized as needed.

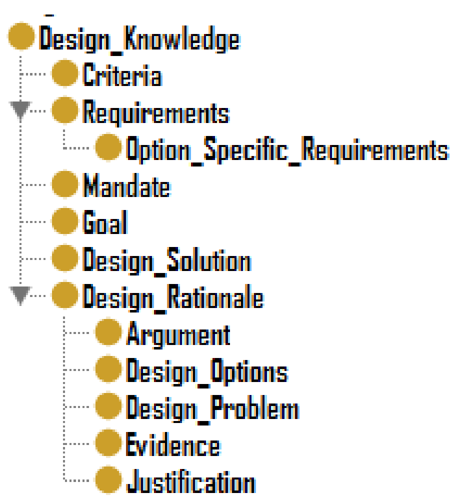


Figure 4-7: Class hierarchy (Taxonomy) for the RaDEX ontology

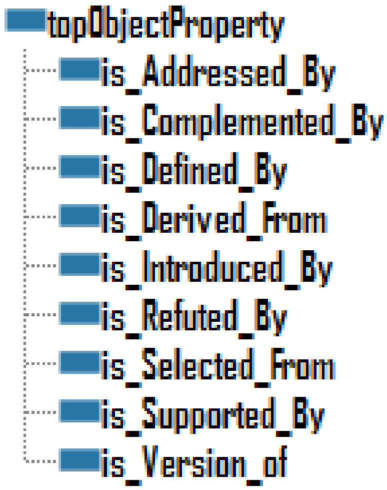


Figure 4-8: Properties/Relationships for the RaDEX ontology

4.4.3 Implementation

Actually developing the ontology using an ontology building environment such as OILed, OntoEdit, Protégé 2000, Ontoloingua Server (Corcho et al., 2003)

An ontology development environment is used to implement the ontology. In this case, the Protégé tool was adopted. Protégé (Protege 2000) is a free, open-source platform that provides a growing user community with a suite of tools to construct domain models and knowledge-based applications with ontologies. At its core, Protégé implements a rich set of knowledge-modeling structures and actions that support the creation, visualization, and manipulation of ontologies in various representation formats. Protégé can be customized to provide domain-friendly support for creating knowledge models and entering data. Further, Protégé can be extended by way of a plug-in architecture and a Java-based Application Programming Interface (API) for building knowledge-based tools and applications.

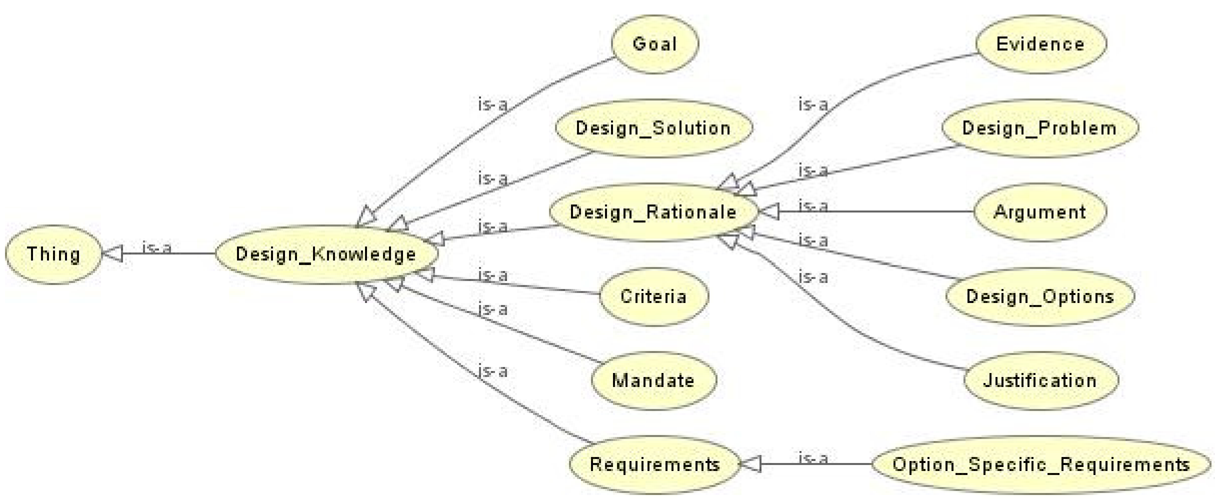


Figure 4-9: Visualization of the ontology from Protégé

4.4.4 Evaluation

Evaluation is done at the end of each phase using the criteria defined shortly in the section below. This is done by having focus group discussions and review with domain experts. A case study is also used to evaluate the ontology and is reported in Chapter 6.

Ontology Design Criteria

(Gruber, 1995) proposes a set of design criteria for ontologies created for the purpose of knowledge sharing. These are described below:

- **Clarity**: An ontology should effectively communicate the intended meaning of defined terms. Definitions should be objective. While the motivation for defining a concept might arise from social situations or computational requirements, the definition should be independent of social or computational context. Formalism is a means to this end. When a definition can be stated in logical axioms, it should be. Where possible, a complete definition (a predicate defined by necessary and sufficient conditions) is preferred over a partial definition (defined by only necessary or sufficient conditions). All definitions should be documented with natural language.
- **Coherence:** An ontology should be coherent: that is, it should sanction inferences that are consistent with the definitions. At the least, the defining axioms should be logically consistent. Coherence should also apply to the concepts that are defined informally, such as those described in natural language documentation and examples. If a sentence that can be inferred from the axioms contradicts a definition or example given informally, then the ontology is incoherent.
- **Extendibility:** An ontology should be designed to anticipate the uses of the shared vocabulary. It should offer a conceptual foundation for a range of anticipated tasks, and the representation should be crafted so that one can extend and specialize the ontology monotonically. In other words, one should be able to define new terms for special uses based on the existing vocabulary, in a way that does not require the revision of the existing definitions.
- **Minimal encoding bias:** The conceptualization should be specified at the knowledge level without depending on a particular symbol-level encoding. An encoding bias results when representation choices are made purely for the convenience of notation or implementation. Encoding bias should be minimized, because knowledge-sharing agents may be implemented in different representation systems and styles of representation.
- **Minimal ontological commitment:** An ontology should require the minimal ontological commitment sufficient to support the intended knowledge sharing activities. An ontology should make as few claims as possible about the world being modeled, allowing the parties

committed to the ontology freedom to specialize and instantiate the ontology as needed. Since ontological commitment is based on consistent use of vocabulary, ontological commitment can be minimized by specifying the weakest theory (allowing the most models) and defining only those terms that are essential to the communication of knowledge consistent with that theory.

This set of criteria has been adopted as guidelines for designing the ontology in this thesis and would be revisited to evaluate the designed ontology.

Other evaluation criteria include adequacy in terms of content; using it in applications or problem-solving methods; and discussing it with experts and eliciting their opinion

4.4.5 Expository Example: Machined Rib Design

This example illustrates the expressiveness of the RaDEX ontological schema described above. A machined rib has no crack stopping features and this means that any crack that develops can extend continuously through the machined rib. This makes the structure sensitive for crack growth and thus less damage tolerant. The goal is to design a machine rib with high stress tolerance to avoid damage.

Figure 4-10 shows two possible alternatives for designing a machined rib. Suppose a designer opts for the second alternative (multiple thickness steps). The rationale for the design choice can be captured and documented using the RaDEX ontology as shown in Figure 4-11. Note that a lower stress concentration (K_t) implies higher damage tolerance.

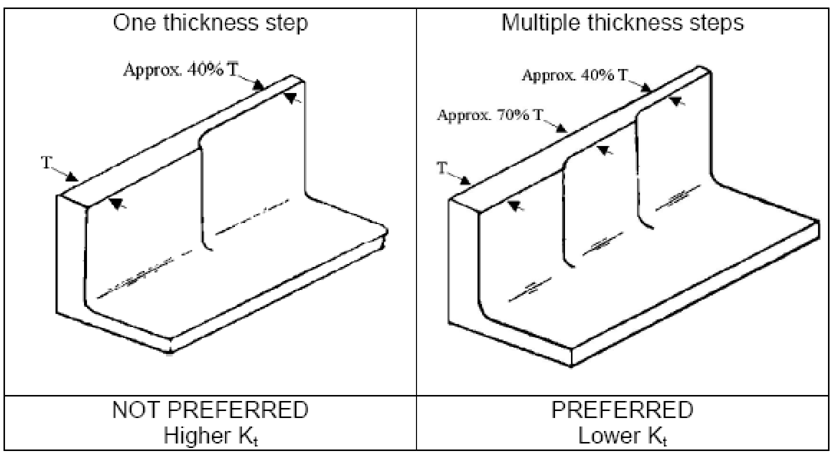


Figure 4-10: Options for flange design (Fokker AESP, 2009).

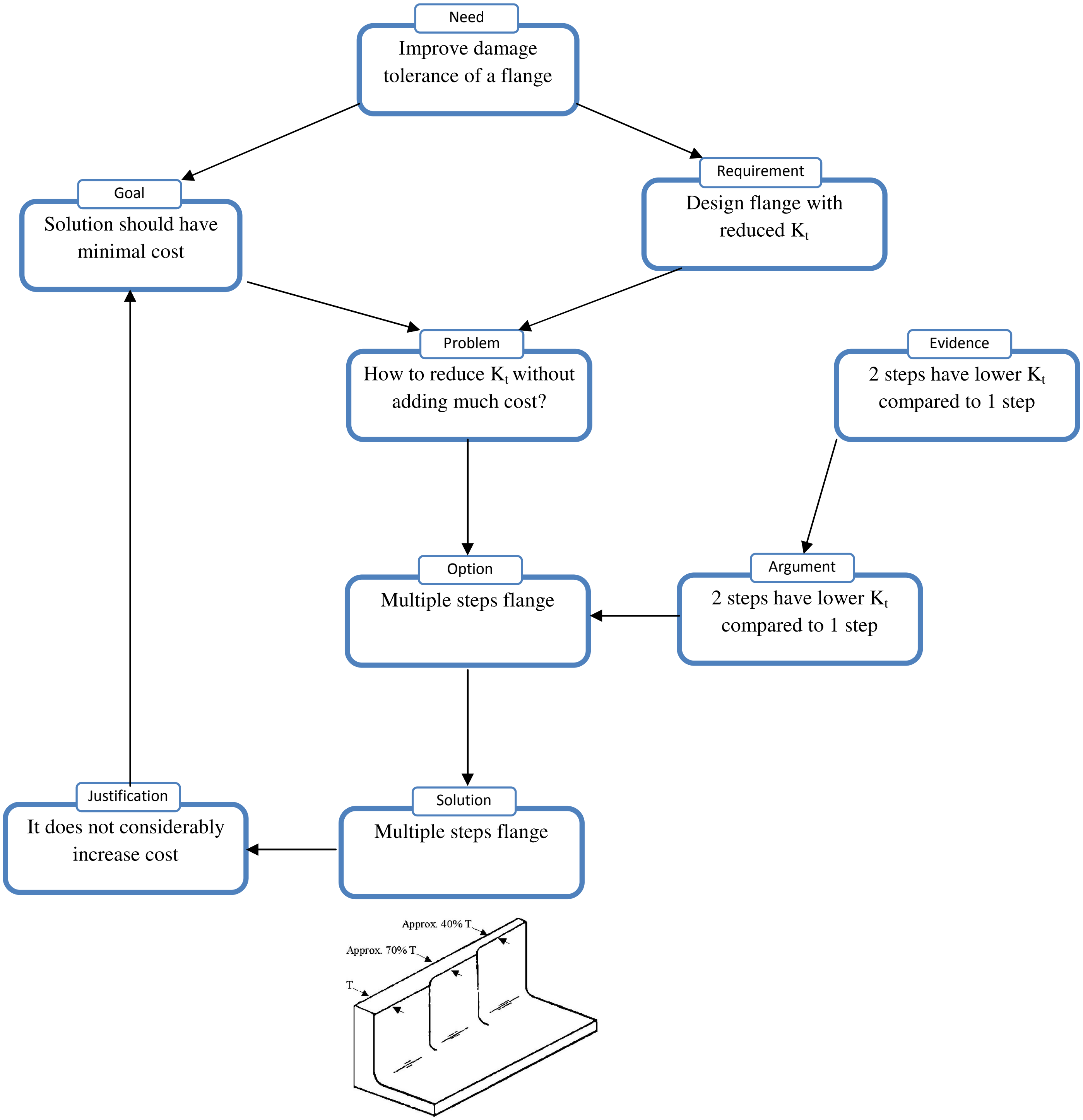


Figure 4-11: Rationale for selecting 'multiple thickness steps' option

5 Evaluation

The evaluation of any artifact after its design and construction is critical to ensure that artifact meets predefined goals and objectives, or adjusted where necessary to optimize its performance in the real world. Recall from chapter 1 the research question:

Is the derived design capture method valid?

- *Can the rationale captured by the method explain designs (effective)?*
- *Is it usable with respect to day-to-day work of designers (efficient)?*

The purpose of this chapter is to address the question by describing efforts aimed at assessing the efficacy of the RaDEX ontology as a representation method for capturing design rationale. The evaluation took the form of a case study conducted at Fokker Aerospace where engineers performed workshop tasks with the method after which a survey was completed to elicit their impressions of the method. Data collected from the survey underlie the analysis that is presented in the chapter. The chapter is structured is follows: Section 5.1 describes the set-up and design of the study, after which the results are presented and discussed in section 5.2. Section 5.3 presents general feedback obtained from the study. Finally, section 5.4 discusses how validity threats were diminished to ensure reliable results from the study; and section 5.5 draws overall conclusions from the study.

5.1 Evaluation Study Design

For this study, a case study research approach was adopted. According to Baxter and Jack (2008), the qualitative case study is an approach to research that facilitates exploration of a phenomenon within its context using a variety of data sources, thereby ensuring that the issue is not explored through one lens, but rather a variety of lenses which allows for multiple facets of the phenomenon to be revealed and understood. This section describes how the study was designed. The participants involved and setting of the study, data collection instrument used and the descriptive statistical methods used to analyze the resulting data are described and presented in the subsequent sub-sections in that order.

5.1.1 Participants and Setting

Invitations were sent to 10 design engineers and knowledge-based engineering practitioners at Fokker Aerospace out of which 6 responded positively. Primarily, design engineers were targeted because of their influence in the design process, and they being the potential major users of the method. Consequently, 5 of the participants were involved in component design with 4 having at least 10 years of design experience. The last participant was a knowledge engineer, with more than 3 years experience, who was included to provide insight from a knowledge sharing perspective. The participants were randomly assigned into one of two teams, A and B, and were introduced to the RaDEX method. The task for team A was to design a horizontal stabilizer rib from a set of requirements, documenting the rationale along the way in accordance with the RaDEX method. With a specification of the designed rib and the documented rationale as inputs, members of Team B were tasked to identify the design choices made by Team A in the course of designing the rib and explain why the design solution turned out the way it did. After their respective workshop tasks both teams were asked to complete a survey to obtain their impressions of the method. A complete description of the assignment can be found in Appendix C. The survey instrument that was used is described in the next section.

5.1.2 Data Collection Instrument and Procedure

A perception-based approach was adopted to assess the impressions of the participants regarding the efficacy of the RaDEX method. The idea of using perceptions for user evaluation of systems or method has been exploited in the past. For example, the Technology Acceptance Model (TAM) (Davies, 1989) relied on user perceptions to predict the adoption of information systems. Building on TAM various other models for perception-based evaluation have been proposed or used to perform user evaluations of developed systems and methods (e.g. D'Ambra & Rice, 2001; Moody, 2003; Condori-Fernández & Pastor, 2008; Santana Tapia, 2009).

In this thesis, we base our evaluation approach on the Method Evaluation Model (MEM) created by Moody (2003). See figure below. The model is largely adapted from TAM, the major difference being the change from the domain of systems to methods.

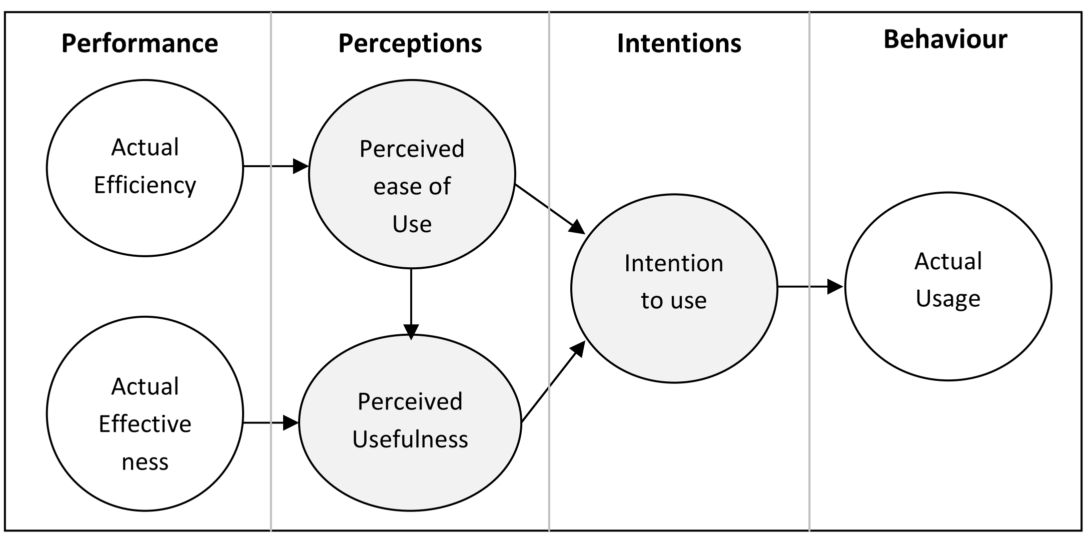


Figure 5-1: Method Evaluation Model (Moody, 2003)

The core of the MEM, constituted by the constructs Perceived ease of use, perceived usefulness and intention to use (the same constructs as in TAM), is what we used in our user evaluation. The constructs are defined as follows (Moody, 2003):

- Perceived Ease of Use: the degree to which a person believes that using a particular method would be free of effort.
- Perceived Usefulness: the degree to which a person believes that a particular method will be effective in achieving its intended objectives.
- Intention to Use: the extent to which a person intends to use a particular method.

These 3 constructs served as the dependent variables for the method evaluation study; the independent variable being the RaDEX method. Based on the variables a survey instrument was designed to measure the perception-based dependent variables, with a total number of sixteen closed questions. The sixteen questions consisted of six items to measure perceived ease of use (EU), eight items to measure perceived usefulness (US), and two items to measure intention to use (IU). The specific set of items for each variable are described below. Actual question numbers as they appear on the post-task survey questionnaire are shown in brackets.

- V1: Perceived ease of use

This variable was operationalized using six items on the post-workshop survey. These items were directly adapted from Moody's (2003) laboratory study meant to evaluate the efficacy of a number of methods.

EU1. I found the procedure for applying the method complex and difficult to follow (Q1)
EU2. Overall, I found the method difficult to use (Q4)
EU3. I found the method easy to learn (Q6)
EU4. I found it difficult to apply the method to the example case (Q9)
EU5. I found the rules of the method clear and easy to understand (Q11)
EU6. I am not confident that I am now competent to apply this method in practice (Q14)

- V2: Perceived Usefulness

This variable was measured using eight items on the post-task survey. These items were also directly adapted from Moody's (2003). The only changes here are in the wording of some of the items to reflect the objective of the RaDEX method which is to capture rationale to improve the explanation of design solutions. The assumption here is that usefulness is defined in terms of how the method achieves its objectives.

US1. I believe that this method would reduce the effort required to document design rationale (Q2)
US2. Design rationale represented using this method would be more difficult for users to understand (Q3)
US3. This method would make it easier for users to verify whether design solutions are correct (Q5)

US4. Overall, I found the method to be useful (Q7)
US5. Using this method would make it more difficult to maintain design rationale (Q8)
US6. Overall, I think this method does not provide an effective solution to the problem of representing design rationale (Q12)
US7. Using this method would make it easier to communicate design rationale to others (Q13)
US8. Overall, I think this method over existing (if any) rationale capture methods (Q15)

- V3: Intention to use

This was measured using two items on the post-task survey. Statements used to operationalize Intention to Use were also adapted from Moody's (2003) laboratory study.

IU1. I would definitely not use this method to document design rationale (Q10)
IU2. I intend to use this method in preference to the standard Entity Relationship Model if I have to work with large data models in the future (Q16)

Responses to the instrument were based on a 5-point Likert scale ranging from (1), "strongly disagree", or the lowest, most negative impression to (5), "strongly agree", reflecting the highest, most positive impression. Following Moody (2003) and Condori-Fernández & Pastor (2008), the order of the items was randomized and some questions negated to avoid monotonous responses. Actual Usage was not evaluated as part of this study, as this was not possible in an experimental context.

5.1.3 Method of Data Analysis

Negative statements in the questionnaire items were reverse coded for analysis. That is, 1 was assigned if the respondent opted for a 5, 2 for a 4; 3 = 3; 2 = 4; and 1 = 5. Descriptive statistics measures, mean and standard deviation were used to analyze the data. The mean, a measure of central tendency, is appropriate for Likert scale questions since the number that is coded can give us a feel for which direction the average answer is. The standard deviation is also important as it gives an indication of the average distance from the mean. A low standard deviation would mean that most observations cluster around the mean. Together, the mean and standard deviation represent a clear overview of the raw data. Furthermore, the total scores for each variable were grouped into 3 clusters: scores of 1-2 indicating a "negative" impression; 3 for "undecided" and 4-5 for a "positive" impression; to ascertain the percentage of responses which fell into each of the categories.

5.2 Results and Discussion

Due to the low number of participants, we take the results of the evaluation as likely indications of reality rather than drawing strong conclusions. In spite of the low small amount of data, the results are still significant since the participants were representative of the stakeholders.

Table 5-1 presents an overview of the mean scores per dependent variable that was measured in the survey. Recall that the perception-based variables give an indication of the ease of use, usefulness and intention to use the method based on the impressions of the participants.

Table 5-1: Descriptive statistics for the instrument scores

Dependent Variable	Experimental Group		Mean Score	S. D.
	Team A	Team B		
Perceived ease of use	3.46	3.42	3.44	0.97
Perceived Usefulness	3.97	3.00	3.48	0.98
Intention to use	4.08	4.00	4.04	0.54

Overall, the mean scores indicate that respondents from Team A who were tasked to capture design rationale using the RaDEX method while designing a horizontal rib rated the method somewhat higher than respondents from Team B. Mean scores for all aspects measured rank above adequate, implying that on a scale from 1 to 5, the method ranks above average. The standard deviations for each of the variables is small (less than 1) indicating that there was a fair consensus among the participants regarding their perceptions of the efficacy of the RaDEX method. For a more in-depth analysis, the responses for each of the variables are described and analyzed in the following subsections.

5.2.1 Perceived ease of use

The tables below display the mean score and standard deviation for each of the items that were used to measure participants' perception regarding *ease of use* of the RaDEX method. Participants from Team A indicated their positive impressions about the ease of use of the method by agreeing (or disagreeing in case of negative statements) most with items E2 and E5: *overall, I found the method difficult to use* and *I found the rules of the method clear and easy to understand.* Also, both items generated a very low standard deviation (0.43) indicating a general consensus among all 4 participants. Items E1, E3 and E4 also scored relatively positive impressions with mean scores of 3.50, 3.50 and 3.25 respectively. The standard deviation for each of these items is also low (less than 1.0) indicating some consensus among the participants; although not as profound as for items E2 and E5. The last item E6 received the least mean score of 3.0, also with a considerably high standard deviation of 1.58, clearly showing the extent of disparity among the scores. A look at the raw scores reveal that half of the participants disagreed with the statement with scores of 4 and 5 while the other half agreed with scores of 1 and 2 (note that E6 is a negative statement). Overall for perceived ease of use, Team A rated the items with a mean score of 3.46, with an overall standard deviation of 0.98. The lowest scores from this team for each of the items were awarded by participant 1, the only knowledge engineer involved in the method evaluation, probably due to his different background. The design engineers together rated the items with a higher mean score of 3.83; and lower standard deviation of 0.7 meaning a higher degree of consensus on their positive impressions about the ease of use of the method.

Table 5-2: Item scores for perceived ease of use - Team A

Number	Questionnaire Item	Mean	S.D.
E1	I found the procedure for applying the method complex and difficult to follow	3.50	0,87
E2	Overall, I found the method difficult to use	3,75	0,43
E3	I found the method easy to learn	3,50	0,87
E4	I found it difficult to apply the method to the example case	3,25	0,83
E5	I found the rules of the method clear and easy to understand	3,75	0,43
E6	I am not confident that I am now competent to apply this method in practice	3,00	1,58
Overall mean and Standard deviation for Team A		**3,46**	**0,98**

Participants from Team B most agreed (or disagreed for negative statements) with items E3 and E6 - *I found the method easy to learn* and *I am not confident that I am now competent to apply this method in practice* – with a mean score of 4.0 each. The standard deviation for both scores was 0 indicating a perfect agreement among the participants on both statements. Items E1 and E5 both obtained a relatively lower mean score of 3.5, also indicating some agreement with the statements. Also, standard deviations in this both cases are 0.5 which mean there is not much disparity among the scores from the various different participants. Items E4 with a mean score of 3; and E2 with a mean score of 2.5 were the least rated of all the items by participants from Team B. In both cases, the disparity among scores awarded by the participants is evident in the relatively higher standard deviations of 1.5 and 1 respectively.

It is interesting to note the differences in ratings from the two teams. For example, Item E2 received a high mean score of 3.75 from Team A but a meagre score of 2.50 from Team B. This suggests that the two teams had somewhat different impressions about the method. This was to be expected since the teams performed different tasks with the RaDEX method. Overall, participants from Team A had a slightly more positive impression of the method regarding its ease of use (mean score of 3.46) as compared to those from Team B (with a mean of 3.42). The results indicate that the RaDEX method is likely easier to capture work with to capture design rationale (which was the task of Team A) as compared to using it to retrieve and use design rationale (the task of Team B)

Table 5-3: Item scores for perceived ease of use - Team B

Number	Questionnaire Item	Mean	S.D.
EU1	I found the procedure for applying the method complex and difficult to follow	3.50	0.50
EU2	Overall, I found the method difficult to use	2.50	1.50
EU3	I found the method easy to learn	4.00	0.00
EU4	I found it difficult to apply the method to the example case	3.00	1.00
EU5	I found the rules of the method clear and easy to understand	3.50	0.50
EU6	I am not confident that I am now competent to apply this method in practice	4.00	0.00
Overall mean and Standard deviation for Team B		**3.42**	**1.00**

With a total number of 6 participants (from both teams) and also 6 items to measure ease of use, this means that there are a total of 36 responses measuring this variable. All 36 responses were categorized as shown in the table below. 7 responses representing 19.44% of the total responses were 1 or 2 (negative impressions), while 24, representing 66.67% were 4 or 5 (positive impressions). The remaining 5 responses representing 13.89% were 3 (undecided). Evidently, two-thirds of the responses suggest that the participants felt the RaDEX method is considerably easy to use to capture design rationale.

Table 5-4: Percentage scores - Perceived ease of use

	Negative (1, 2)	Undecided (3)	Positive (4,5)	Total (1-5)
Score	7	5	24	36
Percentage (%)	19.44	13.89	66.67	100

5.2.2 Perceived Usefulness

Mean scores and standard deviations for items measuring perceived usefulness of the RaDEX method are displayed in the tables below. Again note that for negative statements, scores have been reversed. With average mean scores of 4.25, 4.00, 4.50, 4.00 and 4.25, participants from Team A highly rated the items US2, US4, US6, US7 and US8 measuring the perceived usefulness of the method. This means for 5 out of the 8 items, the participants strongly felt that the method will be useful, while expressing less optimism with the remaining 3 items, US1, US3 and US5 with mean scores of 3.50, 3.50 and 3.75 respectively. Overall, the participants agreed most with the statement indicating that the method provides an effective solution to the problem of representing design rationale (US6); while agreeing least to the statements that the method will reduce the effort required to document rationale (US1) and the method will make it easier for users to verify whether design solutions are correct (US3). Besides US1, scores for all the items also generated a relatively low standard deviation (less than 1) meaning a considerable consensus among all Team A participants regarding their impressions.

Table 5-5: Item scores for perceived usefulness - Team A

Number	Questionnaire Item	Mean	S.D.
US1	I believe that this method would reduce the effort required to document design rationale	3,50	1,50
US2	Design rationale represented using this method would be more difficult for users to understand	4,25	0,83
US3	This method would make it easier for users to verify whether design solutions are correct	3,50	0,50
US4	Overall, I found the method to be useful	4,00	0,71
US5	Using this method would make it more difficult to maintain design rationale	3,75	0,43
US6	Overall, I think this method does not provide an effective solution to the problem of representing design rationale	4,50	0,50
US7	Using this method would make it easier to communicate design rationale to others	4,00	0,71
US8	Overall, I think this method is an improvement over existing rationale capture methods (if any)	4,25	0,43
Overall mean and Standard deviation for Team A		**3.97**	**0.86**

Participants from Team B rated the perceived usefulness items considerably lower compared to the scores awarded by Team A. Only US8: a statement indicating that the RaDEX method is an improvement over existing rationale obtained a mean score of 4.0 (even this is lower from the 4.25 mean of Team A). Items US2 and US5 received the lowest mean scores of 2.50 as the participants thought design rationale represented using this method would be more difficult for users to understand and using the method would make it more difficult to maintain design rationale. Also remarkable is the fact that scores for 4 of the items produced standard deviation of 0.00 meaning a perfect agreement among the two participants who constituted Team B. Again, the data suggests that the RaDEX method is perceived to more useful while documenting design rationale, but less so when retrieving the rationale.

Table 5-6: Item scores for perceived usefulness - Team B

Number	Questionnaire Item	Mean	S.D.
US1	I believe that this method would reduce the effort required to document design rationale	3.00	1.00
US2	Design rationale represented using this method would be more difficult for users to understand	2.50	1.50
US3	This method would make it easier for users to verify whether design solutions are correct	3.00	0.00
US4	Overall, I found the method to be useful	3.00	1.00
US5	Using this method would make it more difficult to maintain design rationale	2.50	0.50
US6	Overall, I think this method does not provide an effective solution to the problem of representing design rationale	3.00	0.00
US7	Using this method would make it easier to communicate design rationale to others	3.00	0.00
US8	Overall, I think this method is an improvement over existing rationale capture methods (if any)	4.00	0.00
Overall mean and Standard deviation for Team A		**3.00**	**0.89**

For a complete overview of all scores for items measuring perceived usefulness, table below presents a categorization of the scores into 3 groups. Out of a total of 48 responses (6 participants and 8 survey items), only 5 were negative representing 10.42 % while 30 or 62.50% were positive impressions about the perceived usefulness of the RaDEX method. 13 of the responses representing 27.08% were undecided. Again, the data shows that a considerable number of responses were positive suggesting that the RaDEX method is likely to be useful in practice as a design rationale representation method.

Table 5-7: Percentage scores - Perceived usefulness

	Negative (1, 2)	Undecided (3)	Positive (4,5)	Total (1-5)
Score	5	13	30	48
Percentage (%)	10.42	27.08	62.50	100

5.2.3 Intention to use

The tables below display the mean score and standard deviation for the two survey items that were used to measure participants' intention to use the RaDEX method to document design rationale in practice. The items received relatively more positive scores as compared to those for perceived ease of use and perceived usefulness discusses above. Participants from Team A expressed strong agreement with the statement indicating that they will definitely use the RaDEX method to document design rationale, with a mean score of 4.50. The statement that they intend to use the method in preference to any existing methods received comparatively less positive score with a mean of 3.67. Standard deviations for the scores for both items were also low (less than 0.5) signifying a fair degree of consensus among participants concerning their intention to adopt the RaDEX method as a design rationale method.

Table 5-8: Item scores for Intention to use - Team A

Number	Questionnaire Item	Mean	S.D.
IU1	I would definitely not use this method to document design rationale	4,50	0,50
IU2	I intend to use this method in preference to existing methods (if any) for capturing design rationale	3,67	0,47
Overall mean and Standard deviation for Team A		**4.08**	**0.69**

Participants from Team B expressed positive impressions about the intention to use the method, both participants assigning a '4' indicating 'agreement' (or disagree for negative statement) to both survey items. The perfect consensus among them is evident in the standard deviations of 0.00 as shown in the table.

Table 5-9: Item scores for Intention to use - Team A

Number	Questionnaire Item	Mean	S.D.
IU1	I would definitely not use this method to document design rationale	4.00	0.00
IU2	I intend to use this method in preference to existing methods (if any) for capturing design rationale	4.00	0.00
Overall mean and Standard deviation for Team B		**4.00**	**0.00**

As shown in the table below, out of a total responses of 12 for items measuring intention to use (6 participants, 2 items), only one response was a 3 meaning 'undecided' This represents approximately 8% of the responses, with 10 or about 83% of the scores being positive. There were no negative responses, with the last response being invalid (N/A). That is the participant did not find that particular statement applicable to his work. Again, this was provided by participant 1 (the knowledge engineer).

Table 5-10: Percentage scores – Intention to use

	No (1, 2)	Undecided (3)	Yes (4,5)	Total (1-5)
Score	0	1	10	11*
Percentage (%)	0	8.33	83.33	

* Total of 11 instead of 12 due to 1 invalid score

The complete datasheet with all collected data can be found in the two tables in Appendix C.3 (one for each team). The tables show the score for all items (coded as EU for perceived ease of use; US for perceived usefulness and IU for intention to use) are indicated. Each column indicates a question or item while each row is a participant. The mean scores and standard deviations are calculated per question and subsequently for each aspect variable.

5.3 Feedback

Aside the 16 questionnaire items which measured the dependent variables discussed above, the post-task survey also included 4 open-ended questions which were meant to elicit general and broad feedback from the participants. There was also, the opportunity for the participants to provide during two separate discussion sessions (one for each team) held shortly after their task was completed. The salient points from the discussion were recorded using a notebook and analyzed.

The RaDEX ontology is structured alongside normal working styles of designers, helping them to explore the design space and properly evaluate their options as they progress from collecting requirements to finding a solution. In this regard, the participants found the approach promising as it did not hinder their actual work but rather improved their overall evaluation of the options. One participant stated:

"By explicitly writing down your design options for the specified requirements and supporting them with arguments, you get to self-evaluate your design choices as you design; and it doesn't slow you down since that's how design is supposed to be done anyway."

However, some of the participants found the presentation layout to be confusing and advocated for an easy way to present the rationale once it has been captured. Suggestions for improvement include to "*think about how to search the captured rationale for solutions, options or requirements."* When specifically asked about what they found most valuable about the method, 3 of the participants pointed out "*the explicit tracking of option specific requirements which are often generated in the course of aerospace design but if not properly documented can lead contribute largely to the inability to explain design solutions*".

Collectively, the feedback received constitutes important considerations for further development of the method.

5.4 Validity Discussion

It is important to ensure that the obtained results are valid. This section discusses important threats related to our evaluation study and the measures put in place to mitigate their effects.

Conclusion validity: Conclusion validity is the degree to which conclusions we reach about relationships in our data are reasonable. Two possible threats to conclusion validity were addressed:

Random heterogeneity of subjects:
Although only 6 participants responded, all the subjects selected for the evaluation study, with the exception of 1, had approximately the same of background namely experience in aerospace

component design. Also, of the 5 designers only 1 had less than 3 years experience with all others indicating at least 10 years experience aerospace design. We are aware that while this homogeneity reduces threats to conclusion validity, it also reduces the external validity of our evaluation study.

Reliability of measures:
We are aware that the perception-based approach is less reliable than using objective measures, since they do not involve human judgment. However, to diminish this threat, we closely adapted the measures from the method evaluation instrument of Moody (2003). Also, due to this we did not address construct validity concerns for the evaluation study.

Internal validity (Instrumentation): Threats to internal validity include effects caused by the s used in the execution of the evaluation study. The tasks for the workshop were supervised by an individual who was conversant with the aerospace design domain; and the survey instrument, along with all other workshop material were verified in advance in order to improve their understandability. It is expected that this will reduce internal validity threats for the study results.

External validity (Interaction of selection and treatment): This is the effect of not having a representative population in the experiment with which to generalize. In our case, we are aware that more studies with a larger number of subjects would be appropriate to reconfirm the initial results obtained.

5.5 Conclusions

The analyses of the evaluation scores for each of the perception-based variables portray a mostly positive impression of the RaDEX method by the workshop participants on all aspects that were measured.

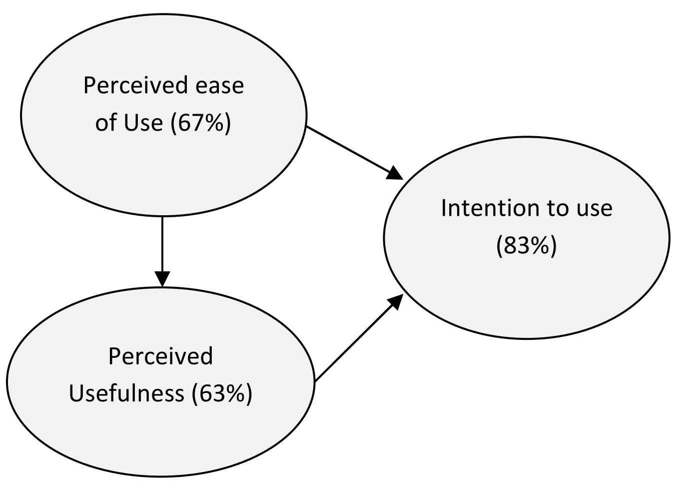


Figure 5-2: Percentage of positive scores for the measured variables

Overall scores of 67% and 63% for perceived ease of use and perceived usefulness respectively point to acceptable levels of efficiency and effectiveness of the method. This means that the process-oriented approach adopted for the RaDEX method makes it quite usable and fits in naturally within the design work. In this case there is little interference of the normal daily work of designers, an assertion that the participants agreed to (as indicated in the feedback section). Also it implies that the content requirements that were derived and applied in this method provided sufficient constructs for capturing design rationale, therefore making the method useful for this purpose. In spite of the positive results, the sum of “negative” or “undecided” scores for each aspect were noteworthy, (33% for perceived ease of use; 38% for perceived usefulness; and 8.33% for intention to use) and suggest that further empirical studies will be necessary to ascertain the efficacy of the RaDEX method in practice.

6 Conclusions and Recommendations

This final chapter reflects on the entire research process upon which the thesis is based and presents the general conclusions and implications of the research findings. Section 6.1 assesses the research process using Hevner et al.'s (2004) design research guidelines. Section 6.2 presents the conclusions drawn from the study by reflecting on the research questions, while sections 6.3 and 6.4 address the contributions and limitations of the research respectively. Next, section 6.5 draws implications of the study for research and practice; after which section 6.6 prescribes recommendations for Fokker Aerospace regarding how to proceed with a design rationale capture solution.

6.1 Evaluation of Research Process

Recall from the introductory section that a design research approach is followed for the research reported in this thesis. This section evaluates the research process using Hevner et al.'s (2004) guidelines as the evaluation criteria. This is to assess whether the research has been carried out in a valid and sound manner with respect to the ideals of a design research. A valid research process is also important as it further enhances the validity of the results or product. The results of the evaluation analysis are presented in subsequent sub-sections.

Guideline 1: Design as an Artifact

Design-science research must produce a viable artefact in the form of a construct, a model, a method, or an instantiation.

This research culminated in the design and construction of an ontology to capture and represent design rationale. The ontology has been created on the basis of existing theoretical foundations and methodologies (drawn from theories of explanation, design and design rationale) and has also been evaluated to ensure its viability.

Guideline 2: Problem Relevance

The objective of design-science research is to develop technology-based solutions to important and relevant business

The entire research was designed and the objectives formulated after the problem domain was properly investigated to indentify and understand the core problems at Fokker to ensure that the direction of the research is focused on solving relevant problems in practice. The problem analysis included interviews with stakeholders such as design engineers, knowledge engineers and others involved in the creation of designs at Fokker. Also, the design aspects of the research were done iteratively, constantly checking with domain experts and stakeholders through, presentations, focus group discussions and reviews to ensure sustained relevance in the solution direction. The end product is a rationale-based ontology (a technology-based artefact) which is proposed as a viable to solving the real problem of explaining design solutions at Fokker Aerospace. The problem analysis is summarized in chapter 1 with other details presented in Appendix A.

Guideline 3: Design Evaluation

The utility, quality, and efficacy of a design artefact must be rigorously demonstrated via well-executed evaluation methods

As described above in guideline 2, Series of presentations, review meetings and focus group discussions were held to iteratively develop and evaluate the ontology from the onset. Finally, a workshop was held where practitioners experimented with the ontology to capture design rationale while carrying out actual design work in a case study. A post-task survey based on an established research instrument from literature was used to measure perceptions of the design engineers. The full report of the evaluation based on the case study can be found in chapter 5.

Guideline 4: Research Contributions

Effective design-science research must provide clear and verifiable contributions in the areas of the design artefact, design foundations, and/or design methodologies.

Several contributions are made through this research, including the RaDEX ontology (artifact). See section 6.3 below for a full description of the major contributions.

Guideline 5: Research Rigor

Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artefact.

The ontology was designed and constructed by relying on theoretical methodological frameworks. The METHONTOLOGY (Fernandez-Lopez, 1999) formed a fundamental framework for designing and implementing the artefact, while a method validation model (Moody, 2003) which is based on the established Technology Acceptance Model (Davies, 1989) was used for its evaluation.

Guideline 6: Design as a Search Process

The search for an effective artefact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.

The search for an effective artefact followed an iterative development approach based on theoretical foundations and methodologies as well as constant evaluation from practice.

Guideline 7: Communication of Research

Design-science research must be presented effectively both to technology-oriented as well as management-oriented

Research process and results are reported in this Thesis Report as well as an internal publication journal at Fokker (Making a Case for Capturing Design Rationale: on problems, applications and benefits of design rationale (Article in Walk E Talk E: Fokker Aerospace Internal publication; April 2010 edition)

In conclusion, all seven guidelines described by Hevner et al. (2004) have been followed in this research meaning that the research has been carried out in an ideal design science fashion and that the study results or product are valid.

6.2 Reflection on the Research Questions

Recall from the introductory section that the central research question for this thesis is:

What is a useful method to capture design rationale to improve the explanation of design solutions?

To answer this question we have explored the very meaning of design explanation by applying various theories (or types) of explanation to the aerospace design domain. The result is a design explanation model which clearly identifies content requirements for a design rationale capture and representation method that is aimed at improving the explanation of designs. Identifying rationale choice as the ultimate decision point leading to design solutions, all other inputs for this rationale decision, including content required for DN, pragmatic and functional explanations are regarded as essential design rationale that must be captured in the course of the design process. A design rationale for explanation is therefore perceived as a record of the dependencies or linkages between requirements, solutions and some specific selection criteria closely related to the original goals of the design.

Based on analysis of the design explanation model, a rationale-based design explanation (RaDEX) ontology is developed as a suitable method to capture and document the required content. This development became necessary after evaluating existing capture method and finding little compliance with the content requirements for design explanation. The methods are largely focused on capturing decisions and their reasoning without paying much attention to the higher level context (requirements, goals, criteria) which are also shown to influence design solutions.

The specific study findings are direct answers to the major research questions that guided the study. These questions are recalled and their answers as presented in this thesis are summarized below:

A. ***What are the problems at Fokker Aerospace due to the lack of design rationale?***
The specific need is identified as the inability to explain design solutions due to the absence of design rationale or the explicit record of the reasoning that led to the design choices.

B. ***What is design rationale?***
Design rationale is seen as all motivating factors that lead to the selection of some design solution that fulfils requirements and satisfies some specific criteria. Design choices are essentially rational decision-making, and this decision along with the inputs for the decision constitutes design rationale. This broadens the scope of design rationale as captured by several existing methods to include contextual elements such as design goals and criteria, requirements and the ultimate need that motivated the design in the first place. Also important is the role of solution specific requirements which essentially are requirements introduced by opting for a certain solution. These requirements show how specific detailed design solutions follow from previously higher-level design choices and provide a useful dependency link for tracing how requirements grow, how solutions mature from concepts into detailed s and the chain of selection criteria that is used at each level.

C. ***How can design solutions be explained?***
Design solutions can be explained by answering the why-question: why is the solution designed this way or why does it look the way it does? These questions can be answered from various perspectives with roots from different types of scientific explanations: DN explanation which explains the outcome in terms of laws or law-like facts, functional explanations on the basis of function statements related to the design choice, pragmatic explanation which explains design choices with respect to relevance and in contrast to other options, and finally rational choice as the ultimate decision point that leads to a deliberate and intentional selection of a design solution from a possible set of alternatives. All these explanation types impose content requirements as to what exactly to capture as design rationale. Hence by developing a method that captures the all the required content, we expect that design solutions will be able to be explained

D. ***What is a suitable method to capture design rationale for design explanation?***
On the basis of the finding in question C above, and the proven inadequacies of existing methods to capture all relevant content requirements, an ontology-based RaDEX method is proposed as a suitable method to capturing design rationale for the purpose of design explanation.

E. ***Is the derived design capture method valid and useful in practice?***
The method is theoretically proven to be capable of capturing all relevant content for design explanation. Furthermore, its efficacy in practice is evaluated from a user or stakeholder

perspective by direct usage in a case study involving actual design tasks. A post-task survey completed by the participants showed promising results for the method.

6.3 Contributions

Recognizing the increasing acknowledgement of the importance of knowledge as a key asset to corporations, and the potential of rationale to make a key contribution toward that knowledge, Burge (2008) underscored the progress that has been made in over 30 years of design rationale research, and called for more attention by the research community to address two issues that she deemed as a major obstacle towards the acceptance of DR:

- We need to understand the needs and problems of the practitioners we are trying to support with design rationale.
- We need to provide more concrete evidence of the value of our solutions through formal empirical evaluations of both existing and new approaches.

In this regard, this study has made 2 significant contributions. First, the research has investigated a method to capture design rationale from a specific use perspective, and that is using design rationale to improve the explanation of design solutions. This objective was determined after analyzing the problem domain and identifying specific stakeholder concerns and goals. The end result is that stakeholders actually see the benefits that accrue from the effort they put in capturing design rationale, leading to the enhancement of the perception towards DR capture and use in practice.

Second, attempts have been made to evaluate the efficacy of the RaDEX method in practice through a case study which involved the use of the method to document rationale in the course of an actual design task. The evaluation exploited a perception-based model (MEM: Moody, 2003) which is based on the more established technology acceptance model (TAM: Davies, 1989) that measures usefulness and ease of use of information systems. Furthermore, existing rationale representation methods have been evaluated through the lens of their expressiveness with respect to content that has been theoretically derived as necessary for yielding design explanations. This can be seen as a theoretical evaluation of the existing methods with respect to some specific needs and problems of practitioners (the need to explain design solutions). This shows that the second issue has been addressed to an extent.

Another significant contribution is the RaDEX method itself, which is essentially an ontology-based approach for representing design rationale. The method incorporates several elements which have been largely ignored or not explicitly captured by previous design rationale representation methods. Evaluation results point to the potential of the method in practice, and requires further development full exploitation to address all stakeholder concerns.

6.4 Limitations

Although the RaDEX method has been designed by following guidelines for effective design research, the method still has some limitations which may have some implications for its practical use.

First of all the research focused only on a representation method for design rationale capture. Besides this, there are the closely related and important issues of acquisition methods for capturing the rationale and methods for effective retrieval and use of the captured rationale. Thus, although the RaDEX method received positive assessments, this implies that there are some limits to the actual efficiency of the method in practice. One aspect of this was evident in the results of the evaluation discussed in the previous chapter, with participants from Team B who had to retrieve and use captured design rationale being relatively less optimistic about the ease-of-use of the method.

Second, due to time constraints we have evaluated the RaDEX method using only a manual version of the method. This might have had an impact of the evaluation results especially with respect to the usability of the method. A software application designed to interface method will likely improve users' perception of the ease of use of the method as compared to the manual approach.

Finally, the method evaluation study involved a low number of participants, with the evaluation instrument measuring only perception-based variables rather than objective, performance-based aspects. This places some limitation on using the evaluation results to strongly predict the actual efficacy and adoption of the RaDEX in practice (although efforts were made to mitigate various threats to the validity of the results – see section 5.4). Hence there is the need to conduct further tests on the method preferably using formal empirical methods to evaluate the method.

Efforts aimed at mitigating the effects of threats to validity also have implications for the method and the evaluation results. By selecting a near homogeneous set of participants for the evaluation study (5 out of the 6 participants were from the same design background) threats to conclusion validity were diminished but this also reduces external validity: the extent to which the findings can be generalized. Thus, little can be said about the impressions of other stakeholders (such as stress engineers or manufacturing engineers) as the participants were not representative of this set. However, important generalizations can be made for design engineers as users of the method.

The RaDEX method was developed by studying and analyzing the aerospace design domain. But with the similar nature of design across all domains (e.g. Architectural design, software design etc as discussed in Chapter 2), the method can well be adopted by designers across all these design domains. Constructs and relationships used in the ontology were directly mapped from the aerospace design process (similar process as in all other domains); and can therefore facilitate the adoption of the method by different aerospace companies or design companies involved in other domains.

6.5 Implications of the study findings

Implications for practitioners: *Link between need/problems and acceptance or tool evaluation*

Organizations embarking on design rationale capture initiatives must do so with the aim of a specific use that addresses pertinent needs and problems of stakeholders. This way, stakeholders are able to directly identify benefits and embrace such initiatives. Only then will the organization also be able to benefit from the knowledge that is captured and stored. Also, by identifying specific use objectives, various tools and methods that have been proposed as design rationale capture tools can be evaluated and only those that meet the specific needs selected. As mentioned in the thesis, there are multiple perspectives of design rationale with different tools attempting to capture what is perceived by the creators as design rationale.

For design rationale aimed at explaining design solutions, the evaluated ontology-based RaDEX method discussed proposed in this thesis is shown to be an expressive and adequate schema that can be adopted. It can be further developed into a complete design rationale capture system with user interfaces to make it easier to integrate with existing design tools and systems.

Implications for further research:

Focus of further research should be on developing a prototype of a complete design rationale capture system with a user interface to the ontology and used in demo projects. This is for the purposes of further evaluation of the efficacy of the RaDEX ontology. Other research issues include addressing specific knowledge acquisition techniques to be used and how the design rationale capture system can be integrated into the existing technical and organizational infrastructure. Finally design rationale retrieval research focused on efficiently accessing rationale captured by the RaDEX ontology will go a long way to ensure that the intended benefits of the system are realized.

6.6 Recommendations: Fokker Aerospace

As indicated in the introductory chapter this research has been carried out at Fokker Aerospace. This section bases on the outcome of the research to prescribe recommendations for the company by way of the next steps to take to move closer to capturing design rationale.

Considering the benefits of capturing design rationale, particularly in terms of reduction in design and production cost and lead-time, Fokker must continue efforts to realize a design rationale solution. Like all information systems a build or buy approach can be adopted to acquire a DR system. Based on the findings presented in this research, a build approach is most recommended. This is because of the positive assessment of the RaDEX method, together with the fact that existing methods did not completely capture all elements which could yield design explanations. The RaDEX ontology, a main outcome of the research is only a skeletal framework that effectively defines the content and structure of design rationale that is necessary to explain design solutions. This ontology can serve as a logical structure for a knowledge-base with a user interface (together forming a complete Design Rationale Capture System) to facilitate the capture, representation and retrieval of design rationale Figure 6-1 depicts the architecture of the system and the interaction within its environment that consists of the existing systems and users. It is recommended that such a system be developed and implemented initially on a pilot basis to serve as a further evaluation of the RaDEX method.

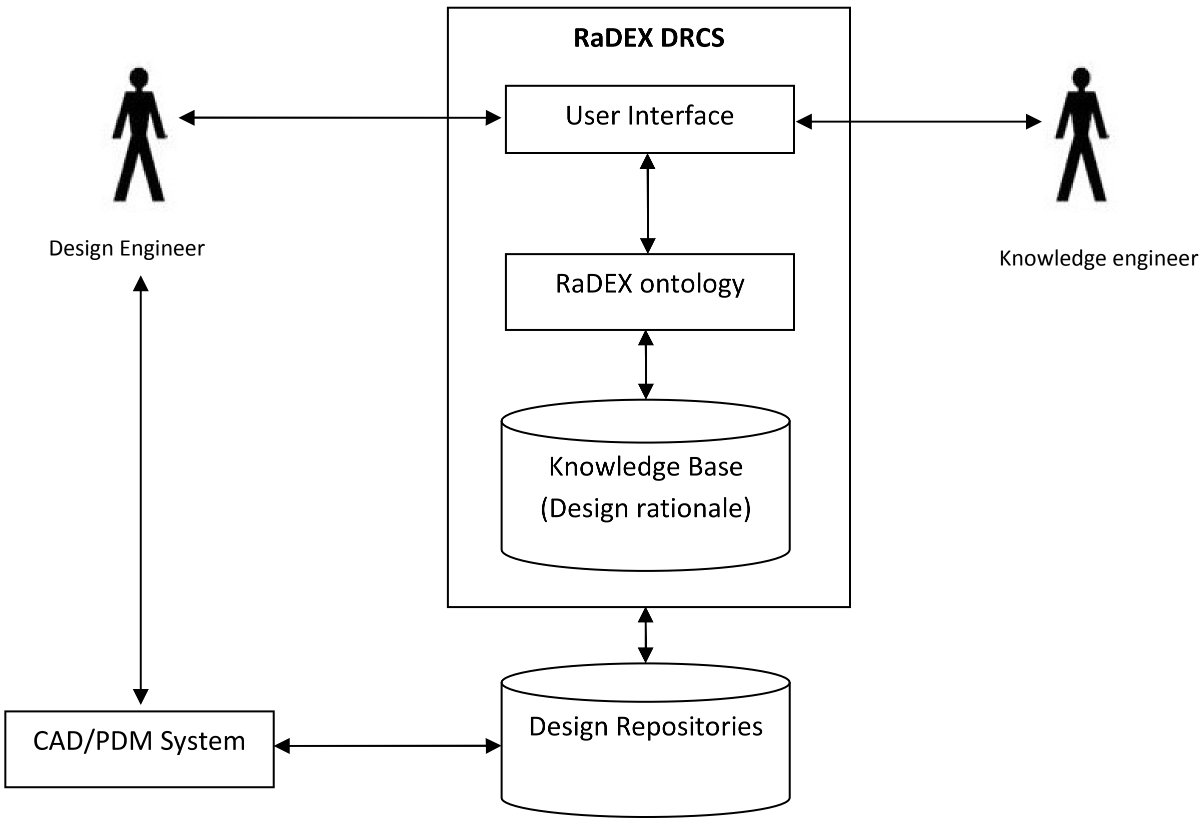


Figure 6-1: RaDEX DRCS Context diagram

In case the buy option is preferred it is recommended that the RaDEX method be used as a selection criterion to evaluate candidate solutions. An ideal solution must be capable of explicitly documenting all content as defined in the Chapter 2 and must capture rationale as a by-product of the design process as this has shown to be perceived favourably by design engineers.

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Appendix A: Problem Analysis Process

This appendix describes the methodology for the problem investigation and analysis presented in Chapter 1. The results of this process formed the foundation of the research reported in this thesis. The description here is intended to give insight into the methodological value of the process and make it repeatable.

A.1 Group Interview-Brainstorm session with experts

A brainstorm Session was held with experts from the Knowledge Management Unit, Tools and Methods Department on 18 February, 2010 at 13:30. The purpose of the session was to establish initial goals for the project and use it to identify starting points to investigate the core problems at Fokker Aerospace.

Participants and Setting

Three experts participated in the session. These include:

Brent Vermeulen, Knowledge Engineer;

Ton van der Laan, Knowledge Engineer; and

Jan Baan, Knowledge Engineer, Conceptual Designer.

All experts were from the Knowledge management unit within the Tools and Methods Department at Fokker Aerospace.

A.2 Interview with stakeholders

Purpose and Objective

The purpose of the interviews was to gain more insight into real and practical instances of the problem(s) experienced at Stork Fokker with respect to capturing and reusing design rationale in the process of designing aerospace components. It is expected that the interviews will be helpful to identify, define and understand the core problem at the heart of the need to capture design rationale. More specifically, the goals of the interviews are as follows:

- To determine the need (relevance) or otherwise of design rationale capture with respect to the stakeholder’s role
- To elicit current issues/practical problems experienced due to the lack of design rationale
- To find out any anticipated opportunities/benefits of capturing design rationale

Participants

As described, the goal of the interviews was to gain more insight into the problem domain and to elicit the opinions of stakeholders on design rationale. The participants were drawn mainly from design engineers at Fokker Aerospace; a few others from other engineering fields were interviewed. Table A.1 below shows the names and background of all participants.

Table A.1: List of interviewees

No.	Participant	Role and Experience
1	Martijn van Rij	Design Engineer, More than 10 years
2	Rene Vrieling	Sustaining (Maintenance) Engineer, More than 10 years
3.	Remi de Groot	Design Engineer, More than 10 years
4.	Barbara Herbsleb	Weight Engineer
5	Onno Verschoof	(Former) Design Engineer, More than 10 years
6	Jeroen Klein Lankhorst	Design Engineer, less than 3 years
7	Barbara Wolters	Stress Engineer

Interview Approach

All interviews were semi-structured and took the following format

a) Introductions (Getting to know each other)

b) Explain goal of research and interview

c) Ask questions

d) Wrap up: explain way forward

e) Future contact to verify findings / seek any clarifications

Interviewees did not have to prepare for this interview, and in spite of the already prepared set of questions, the interviews were of a more conversational nature to drive deeper into issues that come up.

Interview Questions

1. Role and experience in current position?
2. Any prior experience with design rationale?
3. Ever resort to/consult other sources for relevant knowledge (persons or documents)?

- If yes, how often? Is it useful? Why yes? Why not?

4. Any current system/method to capture and store design rationale/knowledge?
   - If yes, why is it useful? Why not?
5. Any practical instances/issues regarding design rationale/knowledge (or the lack of it) and how it influenced your work? → Biggest challenges due to lack of design rationale?
6. Any anticipated opportunities or benefits of design rationale capture? Any added value?
7. Any Design principles/guidelines/procedures?
8. What do you see as an ideal design rationale capture solution?

Results

Responses to the interview questions and other comments and insights were tape recorded and transcribed for analysis. Based on recurring themes, a summary of the results were established. This summary can be found in Section 1.3.2 of chapter 1.

Appendix B: Systematic Literature Review

This appendix describes the methodology and the process of the systematic literature review which is aimed at establishing the 'state of the field' of design rationale research.

B.1 Introduction

A systematic review is a method that enables the evaluation and interpretation of all accessible research that is relevant to a research question, subject matter, or event of interest (Kitchenham, 2004; Kitchenham et al, 2007) Further, Webster and Watson (2002) defined an effective literature review as one that "… creates a firm foundation for advancing knowledge. It facilitates theory development, closes areas where a plethora of research exists, and uncovers areas where research is needed" Thus, a review of prior, relevant literature is an essential feature of any academic project. There are numerous motivations for carrying out a systematic literature review. Specifically for this research this activity aims at the following:

- To review the existing work on capturing design rationale in an industrial engineering context.
- To provide a context/framework for the research project.

B.2 Method

A concept-centric approach (Webster & Watson, 2002) was adopted for the literature review, following a three-stage process proposed by Levy and Ellis (2006). See figure 1 below.

A further breakdown of the stages results in the following systematic literature review steps (Kitchenham, 2007, Pai et al., 2004) which were adopted for this study.

- A comprehensive, exhaustive search for primary studies;
- Quality assessment of included studies;
- Identification of the data needed to answer the research question;
- Data extraction;
- Summary and synthesis of study results (meta-analysis);
- Interpretation of the results to determine their applicability;
- Report-writing.

Search Strategy used for Primary Studies

The search terms or keywords used in the Systematic Review were constructed using the following strategy:

- Derive major terms from the research questions and problem statement
- Identify alternative spellings and synonyms for major terms

- Check the keywords in any relevant papers we already have;
- Use the Boolean OR to incorporate alternative spellings and synonyms;
- Use the Boolean AND to link the major terms

Overall, an iterative approach was adopted by first identifying candidate search terms based on the above criteria and trying them out in various literature indexes. The resulting set of search strings are shown in table 1 below.

Table B.1

Keyword	Query Expression
design	*Design OR Engineering*
rationale	*Rationale OR Knowledge*
capture	*Capture OR Record* OR Document* OR Manage**
method	*Method* OR Approach OR Model*
tool	*Tool OR Software OR System*

Databases and Journals Primary sources were selected based on past work related to systematic literature reviews (Schwartz and Russo, 2004; Webster & Watson, 2002).

- ACM Guide
- Inspec
- EBSCO
- Scopus
- Science Direct

The secondary search phase - The secondary search phase involved a backward and forward search using web of science (Webster & Watson, 2002) to extend the results of the primary studies. This is aimed at identifying other relevant and useful articles which were

Study Selection Criteria and Procedures for Including and Excluding Primary Studies - Initial selection based on title and abstract relevance - design rationale as main issue - preferably including evidence of use in an industrial context. Only scientific articles published in peer-reviewed journals were considered.

Data Extraction Strategy - A concept matrix (Webster & Watson, 2002) is compiled to extract necessary data from the relevant articles retrieved from the databases. The concepts are generated from the problem statement and research questions, and themed according to the popular concepts.

B.3 Results

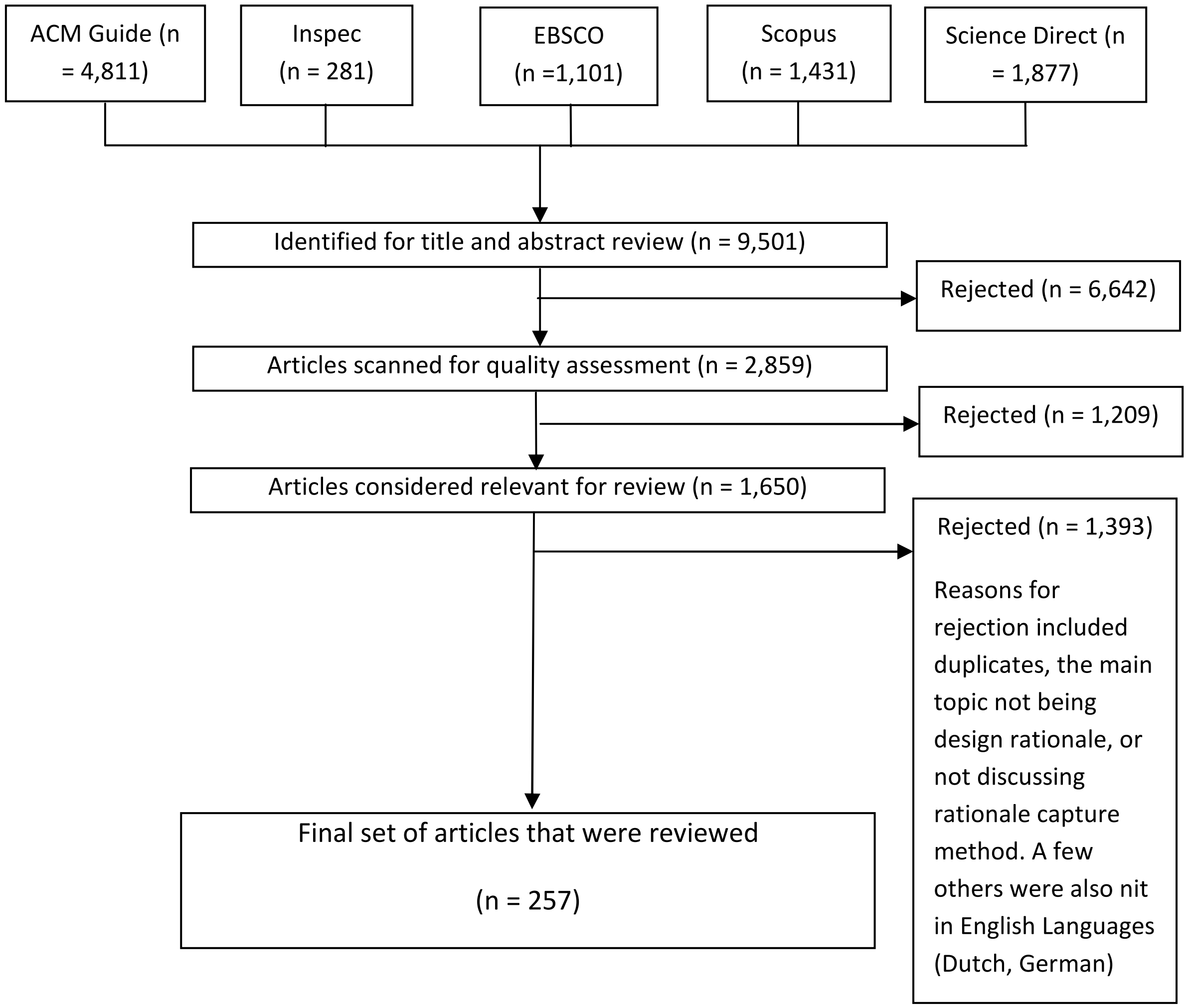

Figure B.1: Search flow for design rationale literature

The articles that were eventfully reviewed formed the basis of the overview of design rationale approaches presented in Chapter 3.

Appendix C: Case Study (Workshop)

C. 1 Workshop Design

Workshop Task

Design, rationalize and explain a horizontal stabilizer rib

Team A

Design a horizontal rib near the root of the horizontal stabilizer. The skins and the spars are Carbon Fiber Reinforced Plastic (CFRP). The rib is a machined rib. All other design choices have not been made yet (For example, orientation of flanges of the spars, type of stringers etc.)

Create the design and rationalize the entire process using the RaDEX method.

Team B

With the designed horizontal stabilizer rib and rationale information as inputs, identify and explain the design choices that have been made in the design of the rib.

Workshop Program

Time (Duration) **13:15 – 14:55**	**WHAT**	**WHO**
12:45 – 15:15	*Setup and arrival (First Team)*	*Ernest/ALL*
13:15 – 13:20 (5 mins)	Welcome and short introduction	Jan
13:20 – 13:30 (10 mins)	Introduction of RaDEX framework	Ernest
13:30 – 14:00 (30 mins)	Design a product (Case) and capture design rationale	Team A
14:00 – 14:25 (25 mins)	Discussion	
Coffee Break		*Team A departs*
14:25 – 14:30 (5 mins)	*Setup and arrival (Second Team)*	
14:30 – 14:35 (5 mins)	Welcome and short introduction	Jan
14:35 – 14:45 (10 mins)	Introduction of RaDEX framework	Ernest

14:45 -15:15 (30 mins)	Make sense of redesigned product and explain design choices	Team B
15:15 – 15:55 (40 mins)	Evaluation and Discussion	All

C.2 Evaluation Questionnaire

Participant Name (optional): ______________________________
Date: ________________
Job Title: ____
Years in present position? <1 1-3 3-5 5+ 10+

INSTRUCTIONS
Please circle your response to the items. Rate aspects of the workshop on a 1 to 5 scale:

1 = "Strongly disagree," or the lowest, most negative impression
3 = "Neither agree nor disagree," or an adequate impression
5 = "strongly agree," or the highest, most positive impression

Choose N/A if the item is not appropriate or not applicable to this workshop.
Your feedback is sincerely appreciated. Thank you.

Part I: Evaluation of Design Rationale Capture Method
(Please circle your response to each item.)
1=Strongly disagree 2=Disagree 3=Neither agree nor disagree 4=Agree 5=Strongly agree N/A=Not applicable

Q1. I found the procedure for applying the method complex and difficult to follow	1 2 3 4 5 N/A
Q2. I believe that this method would reduce the effort required to document rationale	1 2 3 4 5 N/A
Q3. Design rationale represented using this method would be difficult for users to understand	1 2 3 4 5 N/A
Q4. Overall, I found the method difficult to use	1 2 3 4 5 N/A
Q5. This method would make it easier for users to verify whether design solutions are correct	1 2 3 4 5 N/A

Q6. I found the method easy to learn	1 2 3 4 5 N/A
Q7. Overall, I found the method to be useful	1 2 3 4 5 N/A
Q8. I will be able to use what I learned in this workshop.	1 2 3 4 5 N/A
Q9. I found it difficult to apply the method to the example case	1 2 3 4 5 N/A
Q10. I would definitely not use this method to document design rationale	1 2 3 4 5 N/A
Q11. I found the rules of the method clear and easy to understand	1 2 3 4 5 N/A
Q12. Overall, I think this method does not provide an effective solution to the problem of documenting design rationale	1 2 3 4 5 N/A
Q13. Using this method would make it easier to communicate design rationale to others	1 2 3 4 5 N/A
Q14. I am not confident that I am now competent to apply this method in practice	1 2 3 4 5 N/A
Q15. Overall, I think this method is an improvement to existing methods (if any) of capturing design rationale	1 2 3 4 5 N/A
Q16. I intend to use this method in preference to existing means (if any) of capturing design rationale	1 2 3 4 5 N/A

Part II: Open-ended general questions.

1. Describe how you currently capture/document rationale

2. What improvements would you recommend for this method?

3. What is least valuable about this method?

4. What is most valuable about this method?

C3. Evaluation Results Data Sheet

Table C.1 Scores for Team A

	Perceived Ease of Use						Perceived Usefulness								Intention to Use	
Respondent	EU1	EU2	EU3	EU4	EU5	EU6	US1	US2	US3	US4	US5	US6	US7	US8	IU1	IU2
1	2	3	2	3	3	1	1	3	4	5	3	4	5	5	4	N/A
2	4	4	4	2	4	2	5	4	4	4	4	5	4	4	5	4
3	4	4	4	4	4	5	4	5	3	3	4	5	3	4	5	4
4	4	4	4	4	4	4	4	5	3	4	4	4	4	4	4	3
Mean Score	3,50	3,75	3,50	3,25	3,75	3,00	3,50	4,25	3,50	4,00	3,75	4,50	4,00	4,25	4,50	3,67
Standard Deviation	0,87	0,43	0,87	0,83	0,43	1,58	1,50	0,83	0,50	0,71	0,43	0,50	0,71	0,43	0,50	0,47
Mean per Variable	**3,46**						**3,97**								**4,08**	

Table C.2 Scores for Team B

	Perceived Ease of Use						Perceived Usefulness								Intention to Use	
Respondent	EU1	EU2	EU3	EU4	EU5	EU6	US1	US2	US3	US4	US5	US6	US7	US8	IU1	IU2
5	3	1	4	2	4	4	2	1	3	2	3	3	3	4	4	4
6	4	4	4	4	3	4	4	4	3	4	2	3	3	4	4	4
Mean Score	3.50	2.50	4.00	3.00	3.50	4.00	3.00	2.50	3.00	3.00	2.50	3.00	3.00	4.00	4.00	4.00
Standard Deviation	0.50	1.50	0.00	1.00	0.50	0.00	1.00	1.50	0.00	1.00	0.50	0.00	0.00	0.00	0.00	0.00
Mean per Variable	**3.42**						**3.00**								**4.00**	