Engineering Designers' Requirements on Design for Environment Methods and Tools

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This is an academic thesis, which with the approval of the Department of Machine Design, Royal Institute of Technology, will be presented for public review in fulfillment of the requirements for a Doctorate of Engineering in Machine Design. This public presentation will be made at the Royal Institute of Technology, KTH, Stockholm, on 7 June at 14:00

Cover image: Göran Franzén, BT Industries AB

To Jadwiga, Przemek & Alexander

Abstract

Given a special focus on Design for Environment (DfE) methods and tools, the objectives of this thesis are to, *"Identify basic design-related requirements that a method or tool should fulfill in order to become actively used by engineering designers",* and to *"Investigate how those basic requirements could be used to make DfE methods and tools more actively used in industry among engineering designers"*.

The research has shown that designers in general have three main purposes for utilizing methods and tools, of which the last two could be seen as subsets of the first one. The purposes are to: *(1) facilitate various kinds of communication within the product development process*; *(2) integrate knowledge and experience into the methods and tools as a know-how backup*; and *(3) contribute with structure in the product development process*. The low degree of follow-up implies a risk that methods and tools are used that affect the work within the company in a negative way. In order to be able to better follow-up methods and tools regarding both their utilization and usefulness, there is a need for a better definition of requirements for methods and tools.

Most of all designers' related requirements are related to their' aims to fulfill the product performance and keep down the development time. This can be concluded as four major requirements, that a DfE method or tool, as well as a common method or tool, must exhibit: *(1) be easy to adopt and implement, (2) facilitate designers to fulfill specified requirements on the presumptive product,* and at the same time *(3) reduce the risk that important elements in the product development phase are forgotten*. Both these two latter requirements relate to a method or tool's degree of appropriateness. The second and the third requirements are related to the fourth requirement, which is found to be the most important: that the use of the method or tool *(4) must reduce the total calendar time (from start to end) to solve the task.* The conclusion is that DfE methods and tools must be designed to comply to a higher degree with the main users - in this case the designers' requirements for methods and tools.

Key words: Design for Environment, Methods and Tools, Requirements

List of appended papers

This thesis is based on the work described in the following papers, which are referred to by the Roman numerals in the text:

I. Ritzén, S. and M. Lindahl (2001) Selection and implementation – key activities to successful use of EcoDesign tools, Proceedings EcoDesign 2001: Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, Page: 174-179, 11-15 December.

II. Lindahl, M. (2001) Environmental effect analysis – how does the method stand in relation to lessons learned from the use of other design for environment methods, Proceedings EcoDesign 2001: Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, Page: 864-869, 11-15 December.

III. Lindahl, M. and A.-M. Åkermark (2004) Experience of and requirements on methods for product development – An interview survey at a major Swedish vehicle company, Manuscript for journal paper, Linköping, Sweden.

IV. Lindahl, M. (2005) Engineering designers' experience of design for environment methods and tools – Requirement definitions from an interview study, Journal of Cleaner Production, Elsevier, In press.

V. Lindahl, M., L. Skoglund, *et al.* (2003) Use and perception of Design for Environment (DfE) in Small and Medium Sized Enterprises in Sweden, EcoDesign 2003: 3rd International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, Union of EcoDesigners (Association of EcoDesign Societies, Japan), Page, December 8-11.

VI. Lindahl, M. (2004) User requirements for Design for Environment methods and tools – Based on a web-based questionnaire survey, Journal of Sustainable Product Design, Submitted for publication.

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This thesis is, as I see it, not the end but just the beginning of the research journey I want to continue on. However, before doing so I would like to thank all those that have been with me so far, and who have supported, guided and taught me much about how to travel in a safe way and to explore things in order to get as much as possible out of the journey.

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As a novice, it is easy to get lost in the academic world, and I am therefore very honoured to have had Associate Professor Sofia Ritzén as my primary guide and supervisor, who has given me much time, energy and expertise in guiding and reviewing this research. I am also indebted to Professor Margareta Norell's generous support of this work. I would also like to acknowledge Gunnela Westlander for her valuable review of the penultimate version of this thesis, but also for her Ph.D. courses that have taught me a lot and giving me an increased insight in what science and research is all about. At the same time, I want to thank Mica Comstock for his English proofing that has helped me to improve this thesis.

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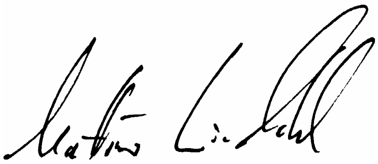
Linköping, March 2005



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Nomenclature

Actively used	When a method or tool is regularly utilized because of a high degree of appropriateness and usability
Appropriateness	The user’s integrated comprehension of the quality of the outcome of the method or tool.
Design for Environment (DFE)	The development of products by applying environmental criteria aimed at the reduction of the environmental impacts along the stages of the product life cycle. (Bakker 1995)
Engineering Research and Education Agenda (ENDREA)	ENDREA was a joint effort between four of the major Swedish institutes of technology: Chalmers University of Technology in Göteborg, the Royal Institute of Technology in Stockholm, Linköping Institute of Technology in Linköping and Luleå University of Technology in Luleå. Funding came from the Swedish board for strategic research, SSF, industry and the participating universities. The main idea behind ENDREA was to create a national cooperation in creating a new type of research in the engineering design area.
Environmental Effect Analysis (EEA)	A qualitative method of assessing the environmental impact of a product, and is intended to be a tool to facilitate companies’ work with environmentally considerate product development. (Jensen *et al.* 2001)
Engineering design	Design with particular emphasis on the technical aspects of a product. Includes both analytical and synthetic activities. (ENDREA 2001).
Environmental impact	Any change to the environment, whether adverse or beneficial, wholly or partially resulting from an organization’s activities, products or services (ISO14041 1998).

LCA	A systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle. (ISO 14040 1997)
Method	A way of working, in a predefined and systematic way, which facilitates the user's work towards a desired outcome.
Product	A system, object or service made to satisfy the needs of a customer (ENDREA 2001).
Product development	All activities in a company aiming at bringing a new product to the market. It normally involves design, marketing and manufacturing functions in the company (ENDREA 2001).
QFD	A method to ensure that a new product satisfies clients. Its goal is to develop an appropriate design and then translate this into targets throughout product development. (Gonzalez and Palacios 2002)
Requirement	A specific description of an attribute of something.
Small and Medium Sized Enterprises (SME)	Enterprises which employ fewer than 250 persons and which have an annual turnover not exceeding EUR 50 million, and/or an annual balance sheet total not exceeding EUR 43 million. (EU 2003)
Tool	A means that, in a predefined and systematic way, facilitates the user's work towards a desired outcome.
Usability	The support to solve a specific task with efficiency and effectiveness.
Usefulness	The combination of two different parameters (even if interlinked) – the ***quality of the method or tool*** and the ***quality of the outcome***.
Utilization	A quantitative measure of the frequency of use, which can be related to the number of product development projects, and which is a function of its ***usefulness***, i.e. whether the method or tool suits the purpose.

Contents

1 Introduction

Scientific research is a continuing and unending search for knowledge and understanding in order to enhance society's knowledge (Wilkingson 1991). Much of this knowledge builds on existing and new methods and tools[1] - methods and tools used to gather more knowledge and understanding in, as it seems, a never-ending process. Blessing *et al.* (1995) state *"the aim of engineering design research is to support industry by developing knowledge, methods and tools which can improve the chances of producing a successful product"*. This can be interpreted as to *develop knowledge, methods and tools, which can improve* ***designers'*** *chances of producing a successful product*. However, apart from a few researchers, for example Norell (1992; 1993), Araujo *et al.* (1996), Cantamessa (1997; 1999), Beskow (2000), Ritzén (2000), Janhager *et al.* (2002) and López-Mesa (2004), relatively few have conducted research concerning the use of methods and tools in industry, and especially not with the designers' use of methods and tools in focus.

The purpose of this research is to, given a special focus on Design for Environment (DfE) methods and tools, increase the knowledge concerning engineering designers' use of methods and tools[2].

1.1. Environmental concerns and industry production

All human-induced environmental impacts are related to products and the use of them. Society's increasing awareness about the connection between products and their environmental impact and related problems has resulted in increasing legal as well as customer demands on a product's environmental performance.

During the last decade, different concepts have been developed to set targets and describe negative environmental impact from products and how they can be re-

[1] Method is defined in this thesis as "*a way of working, in a predefined and systematic way, which facilitates the user's work towards a desired outcome*", and tool as "*a means that, in a predefined and systematic way, facilitates the user's work towards a desired outcome*". Tools are generally based on methods.

[2] "Engineering designers" are herein referred to as "designers".

duced; Sustainable Development[3] (Brundtland 1988), Factor X (Wackernagel and Rees 1996; Weizäcker *et al.* 1998) and Remanufacturing (Steinhilper 1998; Sundin 2004) are some examples. From a Swedish perspective, several product responsibility laws have been implemented, for example those concerning packaging and paper. A major focus in this area, both from legal authorities and industry, has been on "life cycle thinking". The life cycle assessment methodology has also been strongly in focus, and some major Swedish companies have spent considerable funds on this method (Laestadius and Karlson 2001; Cerin and Laestadius 2003).

From a more international perspective, the European Union has developed an Integrated Product Policy (IPP) (Charter 2001; EU 2003). The IPP seeks to minimize products' environmental degradation from manufacturing, use and disposal by looking at all phases of a products' life cycle, and then taking action depending on where the situation is considered to be the most effective. The European Union has also launched a number of different directives, for example those concerning end-of-life vehicles (EU 2000), the Waste Electrical and Electronic Equipment directive (EU 2003) and the restriction of the use of certain hazardous substances in electrical and electronic equipment (EU 2003).

As this thesis concerns engineering designers' requirements on DfE methods and tools, this introductory chapter discusses why this is an important issue to investigate. It begins by introducing the DfE area and the current industrial use and development of DfE. It also describes the reason why designers are key users of DfE, and discusses different ways of using methods and tools that are relevant to consider when identifying requirements. The final part of this chapter describes the objectives, delimitations, and outline of the research work and thesis.

1.2. Design for Environment (DfE)

It has been accepted as fact that the environment would reap positive rewards if more environmental aspects could be considered as far back as during product design, as described, for example, in ISO 14 062 (2002). It has also been estimated that up to 90% of the life cycle cost of a product is determined during the design process (Keoleian and Menerey 1994). According to Ullman's (2002) design paradox, it is essential to learn as much as possible about the evolving product early in product development, because during the early phases of the design process, changes are the least expensive. The later in the design phase environmental issues are introduced, the harder it becomes to implement any changes. Not surprisingly, Bhamra *et al.* (1999) and Ritzén (2000), among others, have argued that environmental aspects need to be integrated into product development as early as possible, and not handled independently.

DfE has become an increasingly important issue for enterprises (DeSimone and Popoff 1997). DfE refers to the systematic incorporation of environmental aspects

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[3] "A sustainable development can be defined as a development that satisfies the needs of today without compromising the possibility of future generations to fulfill their needs". (Brundtland 1988)

into the product design and development[4]. In the literature, there are a number of similar definitions of DfE by, for example, Alting (1993), Ryding (1995), Bakker's (1995) and Ehrenfeld and Lenox (1997). However, Bakker's (1995) definition of DfE is considered by the author of this thesis to be the most suitable in this context, and is therefore adopted here. According to Bakker, DfE is "the development of products by applying environmental criteria aimed at the reduction of the environmental impacts along the stages of the product life cycle (Bakker 1995)". DfE is an approach to design where all the environmental impacts of a product are considered over the product's entire life cycle. The term "life cycle" has been defined according to ISO 14 040 (1997) as "Consecutive and interlinked stages of a product system, from raw material acquisition or generation of natural resources to the final disposal". In both of the definitions above, "product" refers to any good or service.

1.2.1. Method and tools for DfE

During past years, there has been a trend towards the rapid development of methods and tools to employ in the area of product development. According to Mathieux *et al.* (2001), extensive research on DfE, mainly in the areas of strategy, methodology, and tools, has been carried out by research organizations and industrial companies.

The result is a ***considerable number of DfE methods and tools*** as seen in, for example, Simon *et al.* (1998), Wrisberg *et al.* (2000) and Ernzer and Birkhofer (2002). Potential DfE methods and tools fall into a wide range of categories, from relatively simple checklists or general guidelines to more complex software-based decision-making methods (Mizuki *et al.* 1996; Wrisberg *et al.* 2000).

A great amount of relevant literature has been published concerning ***how to perform DfE***, for example Brezet and Hemel (1997), Gertsakis *et al.* (1997), Lewis and Gertsakis (2001) and Ryding *et al.* (1995). The ISO has developed a standard within the ISO 14 000 framework on how to integrate environmental aspects into product development (ISO 14 062 2002).

1.2.2. Use of DfE

Despite the many existing DfE methods and tools, their use is still limited. When they are used, these methods and tools are often not integrated in the product development process. This is a point highlighted by Baumann *et al.* (2002), Ernzer and Birkhofer (2002) and Tukker *et al.* (2000). It was also a finding of the author of this thesis in his parallel research (Ernzer *et al.* 2003; Lindahl 2003).

NUTEK, the Swedish Business Development Agency (2002), had a similar conclusion in its final report on a three-year-long DfE project. According to the report, some large multinational companies (particularly in the fields of electrical and electronic goods, motor vehicles and packaging) are addressing the issue in a rather comprehensive way, and the study concludes that DfE plays a small role in many companies (particularly small and medium-sized enterprises).

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[4] There are also several similar concepts, for example "Ecodesign" (Graedel and Allenby 1995), "Environmentally Conscious Design and Manufacturing" (Matysiak 1993) and "Life Cycle Design" (Keoleian and Menerey 1994).

Some small and medium-sized enterprises (SMEs) have experience with DfE (demonstration) projects, but they rarely lead to the use of DfE in ordinary product development (Hillary 2000; Tukker *et al.* 2000). Further, most companies do not treat DfE as a management issue. Finally, it is common that when a company does practice DfE, the focus is on environmental redesign of products instead of the development of new products. Given this, the potential benefits of DfE have not been realized. The general experience and conclusion of Lenox *et al.* (1996) is that if a company uses DfE, it is usually carried out by those working in specialist functions (i.e. those not involved in the ordinary product development, but those working at the company's environmental division). The results of the DfE work are often not carried back to the rest of the product development process in an efficient way. In many cases, the methods and work with DfE are executed separately from the rest of the product development. This may be a result of the isolation that many methods and tools have been developed in, as described by both Blessing (2002) and Baumann *et al.* (2002).

1.2.3. Isolated development of DfE methods and tools

Even though more and more approaches focus on ***how to perform DfE***, as well as on ***what is required for its successful integration,*** there seems to be a gap between the developers and the presumptive users. Bauman *et al.* (2002) have examined articles[5] concerning methods and tools in the area of environmental product development. These authors carried out a major literature review of approximately 650 research articles. Their literature review began with the impression that there had been a lot of talk about environmental product development over the years. However, what these authors discovered was that most references were conceptual. They also found that there were relatively few references describing the diffusion of DfE methods and tools, the experience of how these tools and methods worked in product development, and how useful these methods were in actually reducing the environmental impacts of products. Baumann *et al.* conclude that most publications with an empirical content report on the testing of new DfE methods and tools, and that these are often developed at universities and tested by researchers in company case studies. This is supported by Tukker *et al.* (2000). They report that many of the DfE methods and tools are developed by researchers within universities or research institutes. In some cases, there is little or no testing of these methods and tools in industrial practice.

Based on their literature review, Baumann *et al.* (2002) conclude firstly that there have been too many normative suggestions with little practical relevance or testing. Related to this, their second conclusion is that there has been an overabundance of DfE method and tool development. According to these authors, the references indicate that those involved in the field are more interested in developing new DfE methods and tools, rather than in studying the use of existing ones in order to evaluate and improve them, as well as evaluating them in accordance with how well they fit into product development.

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[5] Their literature study is based on a cross-disciplinary database containing around 650 research articles, taken from the engineering, management, and policy studies disciplines.

1.3. The designer – a presumptive key user

To achieve a successful product development effort, it is important to make the right decisions from the beginning in order to avoid expensive changes and delays. It is also important to select appropriate methods and tools and, at an early stage, to involve needed competencies (Norell 1992). These competencies, in turn, influence methods and tools selection, and vice versa. Designers, i.e. those who are involved in giving the product a design such as design engineers and industrial designers are a central competence group in product development. Therefore, the position taken in this thesis is that ***designers bring crucial competencies to successful DfE initiatives, and should therefore be important primary presumptive and practical users of DfE methods and tools***. According to Janhager (2002), primary users can be further investigated according to their relationship to a product, in this case the method or tool[6]. Examples of users are the company's management, customers, environment, society and designers. Examples of relationships include use experience, influence on and responsibility for the use, emotional relationship to the method or tool and degree of interaction with the method or tool.

If the ambition is to integrate DfE into ordinary product development – as is the ambition with ISO 14046 (2002) – then ***there is also an essential need to involve and consider one of the main presumptive users of DfE methods and tools: the designer. In fact, it is the designer who is often the main practical executer of methods and tools used to develop a product*** (Janhager *et al.* 2002). Even if designers do not always decide what method or tool to use, their use influences the outcome and the benefits from the use. When using a method or tool, it is important to understand its various advantages and disadvantages. It is also important to know under what circumstances the method or tool's result is valid. This implies that a method or tool is dependent on the user, i.e. whether the user misuses or does not understand how to use the method or tool, or whether the result and/or interpretation of the result will reflect this (Paper III). The method or tool user always has interpretation precedence. It is more or less irrelevant whether the aim of the method or tool developer was to emphasize environmental impact if the user does not realize that, but instead utilizes the method or tool for other reasons, such as, for example, to save costs. In short, what the user interprets is what matters the most.

It is partly because of this that Blessing *et al.* (1995) discuss the difficulties involved in the validation of methods and tools. The success of a method or tool depends not only on the method or tool itself, but also on the context in which it is used. This context is different for every design task, and makes it difficult to generalize the results of an evaluation until the effects and interrelationships of the different influences are known.

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[6] Janhager (2002) has made a classification of users of a product, based on Buur & Windum (1994). A method or a tool is a type of product, and therefore Janhager's classification is relevant in this discussion.

1.4. Utilization and usefulness

The general attitude, in both industry and academia alike, is that design methods and tools are important for improving product development performance. However, the number of methods and tools are broad, and are often met with the mixed attitudes of, for example, enthusiasm, curiosity and skepticism (Beskow *et al.* 1998). According to Ritzén (2000), the usage of methods and tools only becomes a regular activity if they support the users, in this case designers, with their own work. Considering the above in combination with the low level of industry utilization of DfE methods and tools, a developer of DfE methods and tools should consider why DfE methods and tools have such limited use in industry. One possible explanation could be that the DfE method or tool does not fulfill the users' – i.e. designers' – requirements[7]. If so, the application of those requirements could be useful for further development of the DfE method or tool. This thesis deals with the identification of those designer requirements.

Focusing solely on utilization when evaluating different methods and tools may be dangerous. There is a major risk that the wrong conclusions will be drawn, for example what requirements a method or tool should fulfill in order to be regularly utilized. Just because a designer regularly utilizes a method or tool does not necessary imply that method or tool is successfully applied. One example of this is when the utilization is a formal must in the product development process, and the designer considers the outcome useless, already known or not needed for the further product development work.

Another example of when only focusing on utilization is dangerous is when a method provides a useful outcome for a product that is valid for an extended period, perhaps for several product generations. This could imply that the designer does not comprehend any need to utilize the method regularly, even though the outcome is useful[8]. The low or non-existing utilization could also be a result of management issues that prevent the utilization, or because the method or tool is unknown to the designers.

When examining different methods and tools, it important to note and be aware of the fact that their major purposes may differ substantially. For example, the purpose of brainstorming differs greatly from that of various types of DfE tools. Sometimes, the main purpose with the use of the method or tool is not the outcome itself, but rather how the outcome is received.

1.5. Main theoretical concepts used in this thesis

It is the author's conclusion that general methods and tools, as well as DfE method and tool ***utilization***, must be studied and related to the overall context of the situa-

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[7] Requirement is in this thesis defined as "a specific description of an attribute".

[8] However, with this type of utilization, there is a risk that the designer will rely on a previous outcome and his changes imply that the outcome is not valid any longer. In a way, changes will always imply that the outcome changes, but the problem is to know when there is a need for a new updated version.

tion, for example the type of product development or level of education[9]. Utilization is just a quantitative measure of the frequency of use. It is related to the number of product development projects, and is a function of its ***usefulness***, i.e. whether the method or tool suits the purpose. From a designer's perspective, the usefulness of a method or tool depends on two different parameters (even if interlinked): the ***quality of the method or tool*** and the ***quality of the outcome***. Both these two parameters are partly subjective and context-related quality measures, implying that they can be difficult to measure scientifically.

In this thesis, the concept ***usability*** is introduced to describe the user's integrated comprehension of the use-related qualities of the method or tool, for example if they are easy to learn and use. Other qualities are the method's or tool's support concerning efficiency as "*to do things right"* and effectiveness as "*doing the right things"* (Hill 1995). Given this, usability in this thesis is defined as ***"The support to solve a specific task with efficiency and effectiveness"***. High usability refers to when a tool enables its users to generate an outcome in the early phases of the product development process.

Another concept used is ***appropriateness***: the user's integrated comprehension of the quality of the outcome of the method or tool. The quality of the outcome is a combination of factual and subjective aspects, is highly context-related, and is where the satisfaction of the outcome influences the degree of appropriateness. An example of a factual aspect could be that the outcome accuracy is within the limits defined by the customer, while a subjective aspect could be that the user does not consider the outcome reliable. The two different parameters imply that four major types of method and tool usefulness exist, as shown in Figure 1.

The **first type** is when a method or a tool has a high degree of usability, but the designer experiences the gains or appropriateness as low. An occasion when this could be the case is when the use of a method is dictated as a formal "must" in the product development process. Nevertheless, the usability of the outcome for the individual designer is low, for example because the outcome is already known or not needed for further work.

The **second type** is when a method's low usability results in a poor understanding of the method's benefits, and thus low appropriateness.

In the **third type,** the designer's comprehension of the usability is low, but they consider the outcome as having a high degree of appropriateness; one example is a method or tool that is very tricky and complicated to learn and use, but where the outcome compensates for this.

The **fourth type** is the ideal one, and an example of high usability and appropriateness. For example, a designer regularly utilizes a CAD program whose outcome gains the concept of his or her own ideas – a concept that implies further utilization such as an increased degree of usability and appropriateness. This usability and appropriateness, in turn, generates increased utilization. This type of utilization is denoted in this thesis as ***actively used***, and defined as ***"when a method or tool is regularly utilized because of a high degree of appropriateness and usability"***.

[9] See also Paper I.

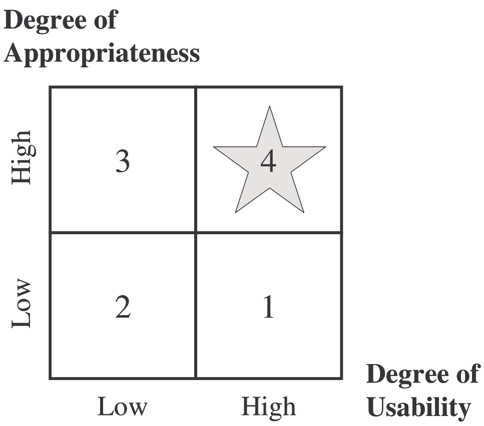

Figure 1. The principal relation between a method or tool's degree of appropriateness and its usability. Degree of usability is related to a method's or tool's support to solve a specific task with efficiency and effectiveness. Degree of appropriateness describes the user's integrated comprehension of the quality of the outcome of the method or tool. The quality of the outcome is a combination of factual and subjective aspects, is highly context-related, and is where the satisfaction of the outcome influences the degree of appropriateness.

1.6. Objectives

The objectives of this thesis are to:

> *Identify basic design-related requirements that a method or tool should fulfill in order to become actively used by engineering designers.*
>
> *Investigate how those basic requirements could be used to make DfE methods and tools more actively used in industry among engineering designers.*

Based on these objectives, four research questions (RQs) are defined in order to further focus the research:

RQ 1. How do designers experience their utilized methods and tools?

RQ 2. What major obstacles for increased method and tool use do designers experience?

RQ 3. What basic method or tool design requirements should a DfE method or tool fulfill in order to become actively used by designers?

RQ 4. How can basic methods or tool requirements be utilized to increase the active use of DfE methods and tools in industry?

1.7. Delimitations

In this research, a number of delimitations have been made:

- During this research, the major focus has been on design methods and tools of *physical* products, i.e. artifacts. Consequently, design of service is not within this research's scope, even though some designers might base some of their comprehension and experience of design methods and tools on their experience with service design.
- This research does not estimate or judge whether the engineering method or tool's outcome from an environmental point-of-view is positive or not.
- The research focuses on engineering methods and tools used by designers *within the product development process*. This implies that many aspects, for example organizational characters of the product development process that have an influence on the use of DfE methods and tools, are not addressed in this thesis.
- In parallel to the above, the research focuses primarily on *designer-related requirements* and needs for methods and tools. Minimal attention, therefore, is put on how those requirements and needs are related to the environment, and how they are affected by other users such managers and society.

1.8. Outline of research work and thesis

This thesis is based on research studies carried out during 2000 - 2004 in a research joint venture between the Department of Technology, University of Kalmar and the Integrated Product Development division at the Department of Machine Design, the Royal Institute of Technology, on how to successfully utilize DfE methods and tools. Figure 2 gives an overview of how the appended papers are used to answer the four research questions of this thesis.

Paper I presents a first outline of selection criteria and procedure, and presents an empirically grounded implementation process.

Paper II concerns a method called Environmental Effect Analysis, and describes the development of this DfE method based on lessons learned from the use of other methods for DfE.

Papers III and **IV** describe designers' experiences with methods and tools. The first of the papers presents a study at a major Swedish vehicle company, while the second paper presents a study carried out at a major international Swedish industrial equipment company.

Paper V, in contrast to those above, presents the use and perception of DfE methods and tools in ten Small and Medium-Sized Enterprises. In comparison to the other appended papers, this paper focuses more on DfE methods and tools.

Paper VI presents a dynamic[10], web-based questionnaire study on the designer's experience with methods and tools. All the papers above have been used as

[10] Dynamic questionnaires, meaning that one answer affected further questions.

a basis for this study. Altogether, the study builds on information from 203 respondents at 24 companies, and with a response rate of 96.1%.

	Paper I	**Paper II**	**Paper III**	**Paper IV**	**Paper V**	**Paper VI**
RQ 1			X	X	X	X
RQ 2			X	X	X	X
RQ 3	X	X	X	X	X	X
RQ 4	X	X	X	X	X	X

Figure 2. Description of how the appended papers support the answering of the research questions.

2 Theoretical Framework

2.1. Product development

According to ENDREA[11] (2001), product development is defined as: "all activities in a company aiming at bringing a new product to the market. It normally involves design, marketing and manufacturing functions in the company".

The rate of market and technological changes has accelerated in the past decade. This implies that companies must be pro-active in the sense that they must be able to rapidly respond to fluctuations in demand (Collaine *et al.* 2002). Central to competitive success in the present highly-turbulent environment is the company's capability to develop new products (Gonzalez and Palacios 2002); to improve, further develop and optimize old products; and to do so faster than competitors (Stalk and Hout 1990). Designers must develop and proceed faster, while at the same time covering an increased number of different demands on the product.

When developing new products, designers typically follow a general procedure, a so-called product development model. A product development model is a process description of the sequence of activities in a company aiming at bringing a new product to the market. It normally involves design, marketing and manufacturing activities. An extensive number of prescriptive models for performing product development have been developed to make product development more effective and efficient; some examples are provided by Andreasen and Hein (1987), Olesen (1992) and Roozenburg and Eekels (1995).

A company's product development model often describes ***which*** methods and tools are used, and ***when*** and ***why*** they are used during the product development process. Thus, the existence of a product development model may give some indication of the formal use of methods and tools among designers.

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[11] Engineering Research and Education Agenda (ENDREA). ENDREA was a joint effort between four of the major Swedish institutes of technology: Chalmers University of Technology in Göteborg, the Royal Institute of Technology in Stockholm, Linköping Institute of Technology in Linköping and Luleå University of Technology in Luleå. Funding came from the Swedish board for strategic research, SSF, industry and the participating universities. The main idea behind ENDREA was to create a national cooperation in creating a new type of research in the engineering design area.

2.1.1. Integrated Product Development (IPD)

The basic idea of the concept of Integrated Product Development[12] (IPD) is to increase the efficiency in product development by more parallel activities and a higher degree of co-operation between functions, levels and individuals in an enterprise (Olsson 1976; Andreasen 1980). The IPD division at the Department of Machine Design, Royal Institute of Technology (KTH), has conducted research on the IPD concept for over a decade, and its researchers have analyzed and defined the concept in great detail described in Norell (1992; 1999), Beskow (2000) and Ritzén (2000). In obtaining efficient product development, integrated work procedures, information management and tools and methods are three crucial elements, as shown in Figure 3 (Norell 1992). Norell (1999) characterizes the performance of IPD as follows:

- Parallel activities
- Cross-functional collaboration by multifunctional teams
- Structured processes
- Front-loaded development

The four characteristics above are in line with what Wheelwright and Clark (1992), Cooper *et al.* (1998), and Wilson *et al.* (1995) regard as important features for successful product development.

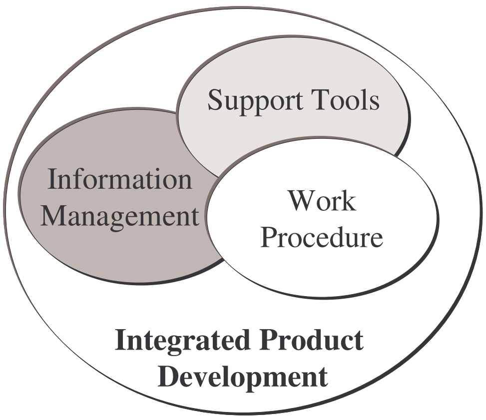

Figure 3. The ingredients of IPD, after (Norell 1992).

2.1.2. The design paradox

When a new design project starts, very little is known about the final product, especially if the product is a new one for the designers. The information accessible is, in

[12] Other similar common terms which correspond to this concept are Concurrent Engineering (Söderved 1991; Prasad 1997) and Lean Product Development (Mynott 2001).

general, only qualitative. As the work on the product progresses, knowledge is increased. At the same time, the scope of freedom of action decreases for every product decision step taken, since time and cost drive most projects. Costs for later changes increase rapidly, since earlier work must be redone (Ullman 2002). The paradox is that when the general design information is needed, it is not accessible, and when it is accessible, the information is usually not needed. This is what is called the design paradox.

Figure 4 shows the principal relation between freedom of action, product knowledge and modification cost[13]. The figure is the author's further development of three figures: the design paradox (Ullman 2002), costs allocated early but used late in the project (Andreasen and Hein 1987) and the cost for design changes as a function of time during the planning and production process (Bergman and Klefsjö 2003).

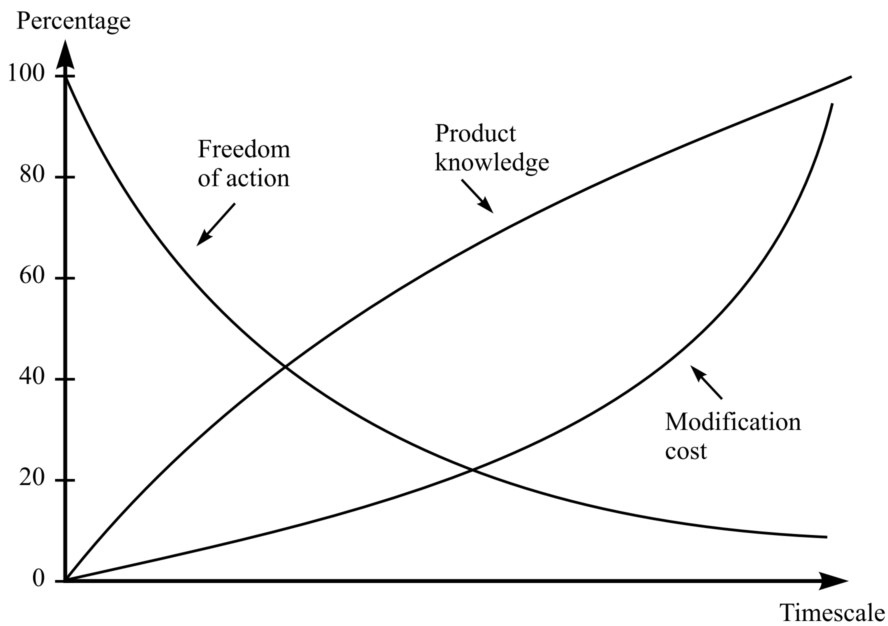

Figure 4. The relation between "Freedom of action", "Product knowledge" and "Modification cost" is shown (Lindahl et al. 2000).

[13] This figure can also be found in the author's licentiate thesis (Lindahl 2000).

2.2. Methods and tools

Work procedures, methods and tools[14], along with information management, are important components in the IPD concept described by Norell (1992). In both academia and industry, methods and tools are considered to be important components in product development performance, and useful to support and speed up work and increase the quality of the outcome (Wheelwright and Clark 1992). This is because of what the support methods and tools give to specific engineering tasks, as well as the platform they provide for discussions and the development of a common language in a product development project.

In this thesis, the concepts "method" and "tool" and their meaning are of central importance, especially given that there seem to be as many kinds of answers to this question as there are authors dealing with methods[15]. According to Cross (2000), some product development methods and tools are innovations of rational procedures, some are adapted from operational research, decision theory, management sciences or other sources, and some are formalizations of the informal techniques that designers have *always* used.

2.2.1. Reasons for using methods and tools

To be beneficial for improvement, a method or tool should offer more functions than strictly technical ones aimed at solving a specific engineering task (Ritzén 2000). According to Norell (1992), they must also support collaboration and promote individual learning. Instead of only solving problems, methods and tools should highlight them, as well as have a measurable effect on the results of project work. They must also, says Norell, fulfill the properties below:

- be easy to learn, understand and use;
- include accepted, non-trivial knowledge;
- be developed for usage by several disciplines; and
- contribute to a systematic work procedure.

The GAPT model[16], as shown in Figure 5, was developed by Hovmark and Norell (1994), and illustrates how methods and tools[17] can be used on different "levels" in the product development process. The higher level of use, according to the GAPT model, the more extensive the consequences for the product development work. The GAPT model can also be used to explain why and how different methods are used within a company.

[14] In IPD, the term "support tools" often includes both methods and tools. Beskow's (2000) definition of a *support tool* is an *"artifact typically in the form of software programs or written guidelines that supports a specific aspect of product development work"*.

[15] See Araujo (2001) for a deeper discussion of this subject.

[16] The abbreviation GAPT stands for Guidelines for design work, Analysis of product features, Product design review and Team-building in design work.

[17] Hovmark and Norell (1994) use the concept "support tool" instead of "method and tool".

T – Team-building in design work.
A larger cross-functional group needs to be set up and the activities need to be well coordinated and planned.

P – Product design review.
More time is needed for discussions concerning ideas and evaluation of suggestions in a larger group.

A – Analysis of product features.
Time is required to carry out a formal analysis.

G – Guidelines for design work.
Training in how to use the method is needed.

Figure 5. The GAPT model (Hovmark and Norell 1994).

Ernzer *et al.* (2002) state that methodical support of the designer is indispensable. Methods are systematic commonsense techniques that aim to bring rational procedures into product development (López-Mesa and Thompson 2002). When selected and used properly, methods have much to offer in, for example, complex multi-objective product design activities. According to Ulrich and Eppinger (2000), methods and tools both control and help to keep direction by:

- Allowing everyone in the team to understand the decision rationale and reducing the possibility of moving forward with unsupported decisions.
- "Acting" as checklists for the steps in a development activity, ensuring important issues are not forgotten.
- Offering structured methodologies which are largely self-documenting; in the process of executing the methodology the team creates a record of the decision making process for future reference and for educating newcomers.

One final argument for the use of methods is that a company whose designers are trained in a wide assortment of methods is a company with high reaction capability to a broad variety of market needs (Beskow 2000; Gonzalez and Palacios 2002).

2.2.2. Current research on use of methods and tools

Numerous new methods and tools for product development have been developed during recent decades to support and facilitate product development (Thoben *et al.* 1997; Collaine *et al.* 2002; Ernzer and Birkhofer 2002; Gonzalez and Palacios 2002). As mentioned in Section 1, a relatively few number of researchers seem to have investigated the use of methods and tools in industry. Little, however, is known and has been published about the extent of their use, the way they are actually used and the impact of this use (Andreasen 2001; Gonzalez and Palacios 2002). Common explanations in research reports, papers and dissertations as to why methods and tools are seldom validated are lack of time and that the validation is outside the focus of the research.

2.2.3. Reasons why methods and tools are scarcely utilized

Reasons found in the literature for why design methods and tools are not more broadly utilized can be divided into two major types: those related to the methods or tools themselves, and those related to their users. These reasons can be translated into requirements that a method or tool must fulfill in order to become better utilized.

Method and tool-related reasons

Previous research from Gill (1990), Andreasen (1991), and Hein (1994) often states that existing methods and tools are not only poorly exploited, but often are in need of reaching a proper form for industrial use. Frost (1999) claims that one of the reasons why methods and tools are scarcely utilized is that academic representations of working methods and tools are very often elaborate representations, based on observations of industry, of what designers in industry have already been doing. More or less in line with Frost (1999) is Cross (2000), who states that methods and tools sometime appear to be unnecessarily systematic or over-formalized to fit into the often rather messy and continuously inconsistent context of the product development. Cross' assertions above are also supported by Blessing (2002), who states that many of the academic method and tool developers seem to work in "isolation", not investigating actual industrial needs. Stempfle and Badke-Schaub (2002) summarize the above in the following statement: "Theory-building and research conducted under the normative strain has often neglected to look at what people actually do – simply prescribing a methodology may not meet the needs of designers out there".

Araujo (2001) has identified additional method and tool-related reasons such as:

- Lack of "appeal" – the method or tool is not adjusted to the needs of the practitioners.
- Poor promotion (marketing) of different methods and tools.
- Too many options – there is a lack of taxonomy and procedures for supporting the assessment and selection of methods and tools

To summarize, many methods and tools have been developed with a scientific and theoretical background, sometimes with little regard for their application in practice (Ernzer *et al.* 2002). Therefore, it is common that methods and tools, for example DfE, are developed to become stand-alone packages, focusing on a single objective such as minimizing environmental impact (Lenox and Ehrenfeld 1995).

User-related reasons

Ritzén (2000) and Araujo (2001) state that the way methods and tools are constructed and implemented is crucial, and influences whether the method or tool will be beneficial and accepted or not. It is, therefore, not beneficial that methods and tools are often introduced by decree rather than by explanation (Ernzer *et al.* 2002). According to Cross (2000), skepticism exists among many designers towards the whole idea of methods and tools. A decree and inappropriate method or tool implementation leads to poor and dissatisfying results, and to distrust of methods and tools among the users in general (Ernzer *et al.* 2002; López-Mesa *et al.* 2002).

In addition, some methods and tools are used at the wrong stage of design, while others are not practiced appropriately (López-Mesa *et al.* 2002). In other words, the users' required knowledge for the successful use of methods and tools is lacking.

Araujo (2001) has identified the following user-related reasons having a negative influence on the use of design methods and tools:

- Lack of reasons and/or interest for methods and tools in order to facilitate product development
- Lack of understanding of the nature of the method or tool – the practitioners are not sure how they can benefit from the available methods.
- Lack of resources for the implementation and use of new methods and tools.
- Fear of change – the impact of the introduction of new methods and tools is understandably difficult to access.
- Negative attitude towards the introduction of new methods and tools – in many cases, this is based on previous bad experience of method and tool introductions.

2.2.4. How companies select methods and tools

A single engineer cannot be aware of all methods and tools that might be useful (Thoben *et al.* 1997). Most companies, says Upton (1997), tend to rely on fairly standard devices, such as method or tool demonstrations (witnessed by engineers), basic cash-flow calculations (calculated by accountants) and "management judgment" (exercised by budget-holders). According to Hein (1994), the source for methods and tools reflects what is currently the practice in the particular branch, supplemented by contemporary enhancement with buzzwords such as total design, QfD, etc. Gonzalez *et al.* (2002), Ernzer *et al.* (2002) and López-Mesa and Thompson (2002) support the statement that method and tool selection is non-systematic.

The designer (Section 1.3) is a key user of methods and tools. For example, even if supporting design methods and tools, engineers follow a careful process to find and select useful methods for the company. This makes little sense if, as López-Mesa and Thompson (2002) found in their survey, designers do not utilize the carefully selected methods and tools. However, Gonzalez and Palacios (2002) state that the selection of methods or tools cannot be left to the preference of designers. Method and tool selection, according to Gonzalez and Palacios, must not only be seen as a bottom-up issue, but also as a top-down one. It is crucial for management, therefore, to adopt a pro-active attitude in this matter. It is the responsibility of management to ensure that the appropriate training is given, and that the methods and tools are used.

2.3. Method and tool requirements

The research mentioned concerning reasons to use methods and tools may be used as an indication of how method and tool requirements should be specified. Method and tool requirements can be useful on two occasions: when developing or improving a method or tool, and when selecting a suitable method or tool. Clear and relevant requirements are essential to ensure that the desired system or product is built, and that the developer or producer, in this case the designer, is not doing more than needed (Hall 1997). In product development in general, there is no question of the necessity of attempting to cover all important and essential requirements, for example as stated by the customer.

Ernzer *et al.* (2002) emphasize the importance of analyzing the company and deriving their requirements for methods and tools. According to these authors, the problem today is not the lack of methodical support for product development, but rather that of choosing the most suitable method or tool, as well as carrying out a detailed analysis of the customer's needs. This is a complex and time-consuming task – and therefore is often neglected.

2.3.1. Identified requirements

Ernzer and Birkhofer (2002) conclude that for the active use of methods or tools in product development, it is essential to select and customize the methods and tools carefully according to the needs of the company. They present different criteria that influence the requirements on a method or tool for DfE, as seen in Figure 6. The criteria are derived from studies, interviews, industry co-operations and literature (Ernzer and Birkhofer 2002).

Product related
- Complexity of products
- Number of pieces
- Dominant life phase

Surrounding environment related
- Laws
- Standards
- Market

Company related
- Competence in e.g. DfE
- Competence in method use
- Degree of innovation
- Resources of the design department
- Strategic targets

Figure 6. Standardized criteria influencing a company's requirements on methods for DfE (Ernzer and Birkhofer 2002).

In order to distinguish between different companies with their corresponding needs, the criteria can be further divided into different qualitative and quantitative characteristics (Ernzer and Birkhofer 2002). Quantitative characteristics are preferable to qualitative characteristics, because they are easier to communicate and evaluate.

By evaluating active use of Design for X (DfX)[18] methods and tools, Huang (1996) has identified a number of requirements that a method or tool should be characterized by:

- Clearly defined, specific areas of concern.
- Logical worksheets, systematic procedures and comprehensive data and knowledge bases.
- The avoidance of unnecessary sophistication in modeling and measuring.

A summarization of requirements that a method or tool should fulfill found in the literature follows below:

- **Integration** – The main idea is working with parallel activities and a higher degree of co-operation between functions. This raises demands on the methods and tools used within this approach (Beskow 2000). A method or tool should promote and work within this draft; it cannot stand as separate activity (Shelton 1994; Lenox *et al.* 1996; Sherwin and Bhamra 1999). If so, the results are likely to be less useful.
- **Multifunctional team** – The method should promote multifunctional teamwork. Wheelwright and Clark (1992), Norell (1992), Cooper (1993), Wilson *et al.* (1995) and Ehrenfled and Lenox (1997) emphasize the importance of multifunctional teams and the exchange of information between different organizational groups. This increases the consciousness and understanding of the problem – and the possibility to solve it.
- **Early phases** – The method should be useful in the early phases of the product development process (Syan and Mennon 1994; Bhamra *et al.* 1999). It is in the early phases where the most efficient improvements can be achieved and should be made. According to the design paradox, improvements become increasingly costly to implement in the latter stages of product development. Other demands on the method, in order to make it more useful in the early phases, are that it should be time-efficient, and that it should be able to handle low-quality data.
  - **Time efficient** – The method must be time-efficient in order to be useful in the early phases of the product development process. This means that the required work input cannot be too high (Ehrenfeld and Lenox 1997); for example, data collection may not take excessive time to accomplish. Furthermore, the time from start to finish must be comparatively short.

[18] Design for X (DfX) is both a philosophy and a methodology that can help companies to change the way that they manage product development and become more competitive. Different DfX methodologies exist where ‘X’ can stand for Environment, Recycling, Assembly, Disassembly, Manufacturing, Remanufacturing etc.

- **Low quality data** – According to the design paradox (Lindahl *et al.* 2000), the accessible data in the early stages of the product development process generally are of low quality (Bhamra *et al.* 1999), and are often only qualitative. The method, therefore, should be able to manage this kind of data. If the method demands a higher level of data precision, the result will be obtained too late in the product development process.

- **Easy to learn, understand and use** – The method should be easy to learn, understand and use (Norell 1992; Ritzén 2000). If not, there is a great risk that the method not will find its way to the people in the product development process, but instead stay with DfE experts at the corporate level (Ehrenfeld and Lenox 1997). In this case, the results will be less useful due to a lack of proper information.

- **Life-cycle perspective** – The method should have a life-cycle perspective, something which is also emphasized by Bakker (1995) and Sherwin and Bhamra (1999). This also reduces the risk of sub-optimization.

- **Marketing aspects** – The method should include marketing aspects, something also emphasized by Bhamra *et al.* (1999). The environmental issues cannot be handled as a single activity in the product development process (Ehrenfeld and Lenox 1997). Instead, environmental issues must be seen as part of many activities, for example quality, cost and safety (Sherwin and Bhamra 1999).

3 Research Method

According to Roozenburg and Eekels (1995), product development is a historic process which cannot in any detail be repeated[19]. The human interaction implies that it is difficult to verify and compare product development in mathematical terms, or by natural science terms that must be replicated to prove a phenomena, event, and experience. Consequently, this obstructs the ability to conduct research in this area.

In the view of the author of this dissertation, a better understanding of designers' comprehension and experience of utilized methods and tools, even if not fully complete, is one way to gain an increased understanding of the context in which methods and tools are used. A context-related understanding that could facilitate the better fit of methods and tools into context would be valuable. Examples of context-related understanding include an increased comprehension of the way designers co-operate, and how much time pressure they have in the situations in which they use the method or tool.

A major challenge for this research has been how to study the low utilization of DfE methods and tools, as this seems to be a major problem in industry. This chapter's first section explains the research strategy to solve this problem. The second and third sections present, in a more practical sense, the selected research methods used in the studies performed.

3.1. Research strategy

Research on environmental issues highlights some risks, for example the fact that people tend to respond to what is assumed as morally good or politically correct in a specific culture/context (Gustafsson 1994). This risk, in combination with the low use of DfE methods and tools, was expected to make it hard to exclusively study these kinds of methods and tools. Instead, in order to obtain a wider perspective on designers' use of methods and tools, and to avoid negatively influencing the respondents, the focus has been on the *general* use of methods and tools. This wider perspective is based on the assumption that the *basic requirements* for any method

[19] This point is obvious, as the opposite would be against fundamental physical laws and imply that it is possible to look into the future.

or tool to become utilized are basically the same. “Requirement” is, in this context, defined as a *“specific description of an attribute of something”*.

The selected objective implies that a descriptive research strategy is more appropriate than a prescriptive, as discussed by Hubka and Eder (1988). The descriptive research strategy selected implies the use of designers’ experience and comprehension of methods and tools (see the research questions that focus on this in Section 1.6), in combination with general guidelines found in the literature (Section 2).

The unit of analysis is the ***designer’s experience of used methods and tools.*** Investigating designers’ own experience of methods and tools is a means for finding industrially applicable methods and tools, i.e. DfE methods and tools. Designers’ requirements for methods and tools can be empirically investigated in several ways; in this research, the following two ways have been used:

- Directly, by asking designers what requirements they have for their methods and tools.
- Indirectly, by asking designers about their experiences with utilized methods and tools, in order to find characteristics that unite these methods and tools and make them easier to explain characteristics that later can be transformed into requirements.

3.1.1. Choice of research methods

Based on the research strategy, which itself is based on the objective and research questions, two types of research methods have been selected: *qualitative research interviews* and *questionnaire studies*.

Based on Beskow (2000), as well as on earlier research and previous experience of low DfE method and tool use, qualitative research interviews were selected since they can be used to explore substantive areas about which little is known, or about which much is known, in order to gain novel understanding (Strauss and Corbin 1998). As the research questions concern “how” and “what” issues, qualitative research interviews have been selected as an adequate approach (See Papers III - V), as discussed in Yin (1994) and Strauss and Corbin (1998).

Ritzén (2000) as well as Beskow (2000) have listed several reasons for using qualitative research interviews, reasons that are also valid for this choice of research method:

- The research area is relatively undeveloped in the academic world.
- There is little practical experience in industry.
- Theory in the area is incomplete.
- The researcher is able to gather several opinions, which give a holistic picture of the phenomena of interest.
- The researcher is able to get a description of actual practice, as opposed to prescribed activities in the industrial product development.

Lazersfeld and Wagner (1958), two founders of sociological study methods, pleaded that exploratory interviews should precede the formulation and final development of questionnaire instruments. The strategy in this thesis has been to use the interviews to build up a knowledge base that, in further steps, can be quantified[20].

3.2. Qualitative Research Interviews

Qualitative interviews have been performed as a means of gaining knowledge about specific problems defined in the design of each research study (see Table 1). Kvale (1983) has defined the qualitative research interview as follows:

> *"An interview, whose purpose is to gather descriptions of the life-world of the interviewee with respect to interpretation of the meaning of the described phenomena".*

Technically, the qualitative research interview is "semi-structured"; it is neither a free conversation nor a highly structured questionnaire. The qualitative research interviews have been conducted following an interview-guide, which rather than containing exact questions, focuses on certain themes.

The interviews were taped and transcribed, word-for-word. The process of data collection has been similar to the sequence presented by Kvale (1997).

3.2.1. Participating companies and interviewed persons

The companies (see Papers III - V) were selected by the author(s) with respect to the criteria that they should have their own product development process and exhibit the use of methods and tools.

Based on the author(s)' earlier experience of co-operation with companies of various sizes, the decision was made to perform the two first surveys at two major companies. A major company can be regarded as consisting of several smaller companies. Coordinating and securing the participation of several companies is more time-consuming and complex, e.g. several managers most approve the survey at their respective companies.

In the second survey (Paper IV), the author learned that the company was looking for new methods and tools in the area of EcoDesign, which had a positive influence on his choice. This also made it likely that the company would accept that the author investigated their designer's experience of existing design methods and tools.

Another important consideration in the selection of companies for the first two surveys was that the companies offered a possibility to, within the same organization, perform interviews at two or three different departments with diverse product types. This reduced the possible negative effects of selecting just one company. The selected departments can be regarded as individual companies within the major company. In fact, in reality the departments described in Paper IV acted more or less individually.

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[20] See Paper VI.

The companies in the third survey, presented in Paper V, were selected based on the size of company. The selection was supported by the University of Kalmar's Industry Contact Department, and was based on information in their database of companies within the Kalmar administrative region. A criterion in the selection process was that the company should be located within this area.

Table 1. Number of interviewees and participating companies in the research studies.

Paper	**III**	**IV**	**V**
Companies	1	1	10
Departments	2	3	-
Interviewed persons	11	13	15
Interview time[21]	1 hour	1 hour	1 hour
Main focus	Design methods and tools	Design methods and tools	DfE methods and tools

3.2.2. Interview guides

Interview guides were developed to set a structure for the interviews. At the same time, as the purpose was to gather information on the subject, it was deemed equally important to let the interviewee bring up his/her subjective experience as to what was relevant and important. The guides used were based on theoretical experience in combination with practical experience. The different studies used different interview guides, although they were the same for each company.

The guide was divided into different subjects, for which different questions were developed. Different conceivable answers to the questions were tested in order to verify that nothing was forgotten. As a final review, all guides (questions) were tested on potential interviewees with similar backgrounds, i.e. designers.

Even though the interview guides' questions varied, the main themes were the same – and so were the majority of the questions. The increased experience about the subject received during the first study (Paper III) resulted in modifications in the following interview guide for Papers IV and V, as reflected, for example, in the greater emphasis on DfE in the study presented in Paper V.

3.2.3. Interviewing

This phase of the qualitative research interview method is the most intricate. It is a balance between the interviewer's own knowledge and experience and the openness to the interviewees' experiences and knowledge. This implies that the interviewer must manage to direct conversations to topics that are not defined in the guide, and at the same time perform a continuous evaluation of the interviewees' responses. In

[21] The average interview time per respondent.

order to better manage this situation, two of the studies (see Papers III and V) were conducted with two interviewers.

Another important issue during the interview situation is to not influence the interview in a negative way, such as through body language or words like “yes” when the interviewee talks. These factors could affect the interviewee and cause them to answer, for example, in a way that he or she believes the interviewer would like. To prevent this, the interviewers studied how to prevent and control this before the interview work commenced.

As expressed above, during the interview situation the interviewer needs to concentrate on the answers received and their analysis. Should the interviewer simultaneously take notes, this might disturb this concentration and at the same time make it impossible to transcribe more than small bits of information to paper. In addition, all pauses, emphasis etc. would most likely disappear. Therefore, all interviews were recorded with high quality sound equipment with noise reduction capabilities in order to obtain a clear recording and thus ease the later transcription. It also enabled the interviewer to recapitulate the interview situation by listening to the recorded conversation, as well as to be able to interpret the meaning of, for example, pauses and emphasis on specific words.

All interviewees were individually interviewed during approximately one hour. Before the interviews, the interviewees were given a brief presentation of the background of the study. All interviews finished with a question: the interviewee was asked to add what he or she thought was relevant yet had not been asked. After the interview was finished, the interviewees were given a more extended background explanation if requested. The reason for this procedure was to limit the risk of influencing the interviewee to give answers in a specific way or with a specific content such as, for example, environmental concerns.

3.2.4. Transcription

The interviews from studies presented in Papers III and IV were transcribed word-for-word into written text by typewriting bureaus. The third study was transcribed word-for-word into written text by the authors. Some minor language corrections were made.

3.2.5. Analysis

As described above, the researchers’ analysis (direct validation) began as early as in the interview process itself, for example during the interviewees’ responses to the specific questions. When relationships and patterns that emerged during the interview became clear to the interviewer, a second validation was made. All taped interviews were then reviewed by the interviewer as the transcribed interviews were read.

The author of this thesis analyzed the interview study presented in Paper IV, as well as the bulk of the interview study presented in Paper III. The study presented in Paper V, in contrast, was analyzed in cooperation with the other authors of the paper.

In the analysis of each study, a comprehensive view of the interview material was obtained. Following this, the focus was changed into certain sub-parts called coding[22] in order to structure the material by using the subjects and themes from the interview guide.

3.3. Questionnaire study

The author has used a combination of Bell's (1993), Ejvegård's (2003), Holme and Solvang's (1997), and Westlander's (2000) ways of performing a questionnaire study. The basis for the study has been the review of the literature, semi-structured interview studies previously performed by the author (see Papers III and IV) and Åkermark (2003), and the author's previous experience within the area as described in Lindahl (2000).

3.3.1. Design of questionnaire

The foundation for the studies has been the literature reviews, the semi-structured interview studies presented above, and the author's previous experience within the area, see Lindahl (2000), Tingström (2003), Åkermark (1999).

Several different types of questions were used (Bell 1993): open-ended, multiple choice, category and scale questions. The questionnaire was Internet-based and distributed electronically via e-mail. Several questions were logical and dynamic questions, meaning that one answer influenced further questions.

Before distributing the questionnaire to the respondents, it was tested by groups consisting of both researchers and prospective respondents. The revised questionnaire was reviewed a final time before it was sent out to the respondents.

3.3.2. Selection of respondents

The aim of the study was to gain a general picture of designers' experience and comprehension of the methods and tools they used, as well as their requirements for methods and tools. In discussion with research colleagues, the author selected the companies based on two criteria. The first was that the company must have its own product development. The second was that the person in charge of the product development process must commit to participating and providing the names of the designers. The companies were also selected depending on size, type and number of products produced, and type of customer. The goal was to get companies with different contexts, based on the aspects above. Altogether, 24 companies (8 major and 16 SME), mainly mechanical, and represented by altogether 203 respondents, participated in the Internet questionnaire study (see Table 2). 187 designers, or 92.1%, answered the survey form. If those who did not complete the entire survey are counted as well, the response rate was 96.1% (195 designers).

[22] Codes are, according to Miles and Huberman (1994), tags or labels for assigning units of meaning to the descriptive information compiled during a study.

Table 2. Number of respondents from different companies. The shadowed lines A-H represent respondents from major companies, while the non-shadowed lines represent respondents from SMEs.

Company	Total number of respon-dents	Number of respondents that …		
		finished the complete survey	started but did not finish the questionnaire	did not answer
A	31	30	1	
B	6	5	1	
C	23	19	2	2
D	16	13	3	
E	5	5		
F	1	1		
G	10	10		
H	20	16	1	3
I	4	4		
J	1	1		
K	1	1		
L	16	16		
M	2	2		
N	3	3		
O	6	6		
P	6	4		2
Q	4	4		
R	5	4		1
S	2	2		
T	11	11		
U	10	10		
V	15	15		
X	1	1		
Y	4	4		
Total	**203**	**187**	**8**	**8**

A problematic question when selecting respondents was to what degree the company had to contribute – i.e. with all of their designers, just some or just a department. Some of the participating companies have thousands of designers, and it was not possible to involve all of them in the project. To make it more complex, some major companies worked like very individual companies within a company, meaning that, in practice, they were more or less seen as two different companies. The decision was made to focus on selecting all or almost all designers from one department at each company. For Small and Medium-Sized Enterprises (SMEs), this implied that, in general, all designers participated.

3.3.3. Distribution and reminders

The study was distributed to the respondents via e-mail, which included an introduction, background on why they received the mail, and information that their head of department sanctioned their participation in the study. They also received information that participation was voluntary, and that the response provided would be handled carefully and confidentially. In addition, respondents were told that neither their company nor their managers were to receive their responses, and that their answers were to be presented aggregated and anonymously in the final report. At the end of the mail, they received a personal code that they could click on to login and start the Internet study.

After three weeks, the respondents received the first reminder, and after another two weeks, the second and final reminder. In every reminder, respondents received the code that they could click on to begin the study.

3.3.4. Data analysis

The analysis was performed in several steps, and SPSS for Windows version 11.5.1 and Microsoft Excel 2000 were used as supporting tools in order to manage data for the empirical material analysis.

In the first step, the different questions and answers were analyzed individually. In the following step, different questions and answers were related to one another in order to find patterns and connections.

The author of this thesis performed the majority of the analyses. However, valid comments and support on some issues were also received from other researchers.

4 Summary of appended papers

This thesis is based on the work described in the appended papers, which are referred to by the Roman numerals in the text.

4.1. Paper I – Selection and implementation – key activities to successful use of EcoDesign tools

(Ritzén, S. and M. Lindahl (2001) Selection and implementation – key activities to successful use of EcoDesign tools, Proceedings EcoDesign 2001: Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, Page: 174-179, 11-15 December.)

The first paper of this thesis was co-authored with Ritzén, its primary author. Lindahl was responsible for Section 3 – selection of tools – but influenced the other sections as well.

Purpose

Methods and tools are selected in conformance with a specific organization's needs, and are implemented in a conscious and reflective way. This paper's purpose is an attempt from its authors to place focus on how methods and tools could be an effective way to integrate environmental aspects into product development.

Research approach

Previous research studies conducted by the authors, namely those found in Ritzén (2000)[23] and Lindahl (2000; 2001)[24], together with a literature review, constituted the basis for the paper.

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[23] The research's principal data collection method was based primarily on qualitative research interviews.

[24] The research was a mix of literature studies, practical tests of the method described and workshops with designers.

Results

In short, the paper consists of two parts. The first part presents the first outlines of a conceptual tool and method selection procedure, while the second part describes an empirically grounded implementation procedure developed specifically for this research. The proposed tool and method selection procedure consists of seven different described steps, and the presented implementation procedure is connected to this procedure.

The authors' own research, in combination with the reviewed literature, shows that the development and application of methods and tools are often prioritized efforts for the improvement of product development performance, as well a way to integrate environmental aspects. To support the integration of environmental aspects, an extensive number of DfE methods and tools have been developed. Thus, many companies tend to select and apply a certain method or tool to introduce a new perspective in their product development; however, a regular use that actually contributes to environmentally improved products is not a direct result. The method and tool selection is, in general, unstructured and haphazard, and seems to depend more on if the method or tool is poplar at the moment than on an analysis on how well the method or tool suits the purpose.

Conclusions

In order to gain successful use of methods and tools, a careful selection process and conscious implementation must be applied. The determination and assessment of requirements for methods and tools needs more research, and thus the development of context-bounded requirements are proposed. Examples of context-bounded requirements could be type of product or degree of integration.

The development of method and tool criteria (requirements) will also contribute to defining success factors for method and tool application, something that can aid both product developers (users of methods and tools) as well as method and tool developers.

Contribution to the thesis

The overall discussion in the paper has influenced the following papers, and consequently the overall structure of this thesis. One example of a direct contribution to this thesis is the discussion concerning the requirements for methods and tools found in the literature.

4.2. Paper II – Environmental effect analysis – how does the method stand in relation to lessons learned from the use of other design for environment methods

(Lindahl, M. (2001) Environmental effect analysis – how does the method stand in relation to lessons learned from the use of other design for environment methods, Proceedings EcoDesign 2001: Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, Page: 864-869, 11-15 December.) ***Received Best Paper Award.***

Purpose

The second appended paper of this thesis had two purposes. One was to sum up the lessons learned from the use of methods and tools for DfE (DfE). The other was to compare how the author's further development of a DfE method, the Environmental Effect Analysis (EEA), stands in relation to these lessons.

Research approach

In order to find lessons learned of method and tool use with special focus on DfE, an extensive literature review was conducted. Examples of reviewed literature include books, reports, articles and conference papers. References found in the reviewed literature were also followed up, as were lessons learned from the author's practical experience from EEA methodology case studies.

Results

Several lessons learned are described and discussed. For example, the importance of integration with the ordinary product development and the need to be involved in its early phases, and therefore increase time efficiency in the product development process was seen. The paper also contains a description of the EEA method, and how it has been further developed in an interactive process based on knowledge and experience from the literature review and case studies.

Conclusions

It is in the earliest phases of product development where the most efficient changes and improvements can be achieved and should be made. A method or tool, therefore, should be useful in the early phases of product development. Furthermore, a method or tool should promote and work within the integrated product development draft, as well as promote multifunctional teamwork. To summarize, the EEA method corresponds well with the way a method or tool should be in respect to the lessons learned identified from the use of other DfE methods.

Contribution to the thesis

This second paper illustrates how a method for DfE has been further developed based on lessons learned from the literature. Of special importance to the thesis are the lessons learned from the literature review.

4.3. Paper III – Experience of and requirements on methods for product development – An interview survey at a major Swedish vehicle company

(Lindahl, M. and A.-M. Åkermark (2004) Experience of and requirements on methods for product development – An interview survey at a major Swedish vehicle company, Manuscript for journal paper, Linköping, Sweden.)

Lindahl and Åkermark shared the responsibility for study design and data collection in this third appended paper. Lindahl was responsible for analyzing and writing the paper, while Åkermark supported in the writing and analysis work.

Purpose

The purpose of Paper III was to describe how the actual users, in this case designers, experience and use methods and tools. A parallel purpose was to identify requirements that designers consider a method or tool ought to fulfill.

Research approach

The empirical base for this paper was a qualitative, semi-structured interview study conducted during the spring of 2002 at a major Swedish heavy vehicle company. Eleven designers working with product development from two different plants were interviewed regarding their experience of methods and tools, with a focus on methods and tools used.

Results

A literature review highlights different aspects of methods and tools, such as reasons for using them and their low level of use. Results regarding designers' use of different methods and tools are presented, as well as a discussion of how they are experienced.

One reason why so few methods and tools are used is the implementation cost in training, loss of working hours and initial lowered productivity when using the method or tool. Another reason is that designers do not search for new methods and tools unless they really need them, and have the time to reflect on those they have used. Finally, the enormous number of existing methods and tools makes it impossible for a single designer to be aware of all that exist.

In addition, different requirements that designers experiencing a method or tool ought to fulfill in order to be useful are described and discussed.

Conclusions

Methods and tools, despite minor shortcomings, generally satisfy their users. At the same time, these users may experience a lack of follow-up for the methods and tools they use. The reason found for using methods and tools is to gain *more efficient product development*, and the means to attain this is through *better structure.*

Additional studies covering a large number of designers and companies are needed to be able to describe, in quantitative terms, more general characteristics of methods and tools actually used.

Contribution to the thesis

This third paper's contribution to the thesis consists of results and discussion concerning how and why methods and tools are used by designers. Furthermore, another contribution is the conclusions about what makes a method or tool actively and regularly used by designers, and their additional need experienced for more methods and tools.

Finally, the conclusions about designers' experience of utilization of methods and tools in combination with designers' requirements on methods and tools results in, for this thesis, important conclusions about designers' requirements for what methods and tools should fulfill.

4.4. Paper IV – Engineering designers' experience of design for environment methods and tools – requirement definitions from an interview study.

(Lindahl, M. (2005) Engineering designers' experience of design for environment methods and tools – Requirement definitions from an interview study, Journal of Cleaner Production, Elsevier, In press.)

Purpose

The purpose of the study was to identify designers' experience of utilized methods and tools and the requirements for these. The following questions were of interest:

- What are the aims of utilizing methods and tools?
- Who is involved in the utilization of methods and tools?
- Who decides which methods and tools to utilize?
- What makes a method or tool actively used?
- What formal and informal requirements and wishes do designers have for methods and tools?

Research approach

Semi-structured interviews were carried out with 12 designers at a major international Swedish industry equipment company, with a focus on utilized methods and tools. A major assumption was that the basic requirements for a method or tool to be used were the same.

Results

Methods and tools are used to facilitate various kinds of communication within the product development process. Designers are the main actors in the utilization of methods and tools, with quite low co-operation from other departments. Designers are for the most part very free to select which method or tool to utilize, and their frequency of utilization of different methods and tools is interpreted to relate to four main topics: (1) to what extent the method or tool is experienced as beneficial; (2) whether the utilization of the method or tool is in one way or the other required by the customer; (3) the method or tool's primary purpose, and (4) its level of complexity (must not be unnecessarily complicated to use).

Several designer method and tool requirements were highlighted, namely that a method or tool must be: easy to understand and experience its benefits, easy to understand how the method or tool is working, adjustable to different contexts and does not require extensive cooperation.

Conclusions

From the respondents' point of view, methods and tools are utilized to facilitate communication within the product development process, with the aim to save time in order to be able to accomplish more. Designers are looking for general guidance rather than specific direction. A mix of four reasons influence whether a method or tool becomes actively and regularly utilized:

- The designer experienced the method or tool to be beneficial.
- The customer requires the utilization of the method or tool.
- The method or tool covers relevant issues handled on a daily basis.
- The method or tool is not experienced as being unnecessary complicated to utilize.

Selection and implementation of methods and tools should occur in dialog between designers and management, and ought to be a balance between the company's goals and the primary user's, i.e. designer's, goals. Paradoxically, methods and tools used in product development to handle products' formal and informal requirements and wishes seem to be developed, selected and used without formal requirements and wishes.

Contribution to the thesis

This study contributes to this thesis in several aspects, for example the results and discussion about how and why methods and tools are used, as well as the discussion about what make a method or tool actively and regularly utilized. Finally, important contributions are also reflected in the discussion of designers' requirements and the level of follow-up of utilized methods and tools.

4.5. Paper V – Use and perception of Design for Environment (DfE) in small and medium sized enterprises in Sweden

(Lindahl, M., L. Skoglund, et al. (2003) Use and perception of Design for Environment (DfE) in Small and Medium Sized Enterprises in Sweden, EcoDesign 2003: 3rd International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, Union of EcoDesigners (Association of EcoDesign Societies, Japan), Page, December 8-11.)

In Paper V, Lindahl, Skoglund and Svensson shared the responsibility for the study's design. Skoglund and Svensson preformed the main data collection and transcription of the interviews, while Lindahl, Skoglund and Svensson shared the responsibility for the analysis. Karlsson supported in the analysis, Lindahl wrote the paper.

Purpose

Product development is an essential issue to achieve sustainability, and it is important to study product environmental performance in a life cycle perspective and to work with DfE. Nevertheless, what does it take a company to consider environmental aspects when developing products? What motives are there to use DfE? Is there a will to work with DfE? Given these questions, the purpose of the study described in Paper V was to increase knowledge concerning the expressed and unexpressed needs of product developing companies for DfE.

Research approach

In order to map and analyze accessible DfE methods and tools, the starting point was a literature review. The investigation of need and interest for DfE occurred through qualitative, semi-structured interviews with a total of fifteen persons at ten small and medium-sized companies with product development in the region of Kalmar, Sweden. During the interviews and literature review, the issue of DfE connected to questions like sustainable development, economic aspects, quality and business development was a focus.

Results

The smaller companies seldom used methods and tools, and it seems that the larger the company was, the more complex the methods and tools that were used. Various Computer-Aided Design (CAD) programs were the only more or less utilized methods and tools among the companies investigated. Some of the medium-sized companies had previously tried to use DfE methods and tools, but they were no longer in use and there was no stated need or perception of any methods or tools, including DFE. Several of the smaller enterprises felt that methods and tools made the work more complicated and bureaucratic. Utilization of methods and tools are time-consuming tasks that must relate to the benefits. Lack of knowledge about methods/tools and funding are examples of aspects that prevent designers from using methods and tools. There is a very clear image that environmental issues are rarely, if ever, a driving force. This implies that the demand for DfE is weak, and that according to the author's view, the need for DfE methods and tools is low. Several requirements stated for "good" methods or tools were identified.

Conclusions

The DfE method and tool utilization was found to be zero, and there was no major stated need for DfE tools and methods at the companies. It seems to be important to clarify the integration and correlation between environmental considerations and other business considerations. It is also important to develop methods and tools that really are adjusted to the needs of the companies.

Contribution to the thesis

This paper contributes with input on why the method and tool utilization at the companies was low, and in particular for the use of DfE. Motivation for the use and need of DfE methods and tools are an important aspect when discussing designers' use of methods and tools. Even though an individual method or tool fulfills all the requirements stated by a user, it is irrelevant unless there is a need for the method or tool.

4.6. Paper VI – User requirements for Design for Environment methods and tools – Based on a web-based questionnaire survey

(Lindahl, M. (2004) User Requirements for Design for Environment methods and tools – Based on a web-based questionnaire survey, Journal of Sustainable Product Design, Submitted for publication.)

Purpose

The purpose of this study, described in the final appended paper of this thesis, was to identify the requirements a DfE method or tool should fulfill in order to meet designers' requirements. In this case, the following research questions were of interest:

- How do designers experience the use of utilized methods and tools?
- How do designers reflect on their increased understanding of utilized methods and tools and the education that they receive regarding utilized methods and tools?
- What are designers' general requirements on methods and tools?

Research approach

Based on the objective and the attempt to obtain general and quantitative information from many designers at different companies, the selected research method was a web-based questionnaire study with both qualitative and quantitative questions. The research method enabled the use of dynamic questions in a structured way. Altogether, 24 companies (8 major and 16 SMEs), mainly mechanical, were represented by 203 respondents. 92% answered the questionnaire, and if those who did not complete the entire study form are counted as well, the response rate was 96%.

Results

A vast majority of the designers experienced a great possibility to influence the use of methods and tools. The most widely used methods and tools, other than various CAD tools, were Brainstorming, FMEA, LCC, DfA and EEA. Of those methods and tools, only CAD, Brainstorming and FMEA were used at the majority of the companies. When focusing on the DfE-related methods and tools, the only ones mentioned as used were EEA and LCA.

Only 9% of those designers who used methods and tools knew that unsuccessful use was documented and analyzed, while 59% did not know whether there was any follow-up or not. Of the 175 respondents that used one or more methods or tools, 53% responded that requirements that the method or tool must fulfill to be selected and implemented existed. Of those respondents that claimed determined requirements existed, 69% responded that those requirements were documented, 16% claimed that they were not, and 15% did not know.

The respondents validated 32 different alternative statements about methods and tools that can be interpreted as requirements[25].

Conclusions

The general need for more methods and tools is high. Respondents' experiences were that their individually most-used method and tool quality was, in general, high. The method and tool education they received was appreciated, but several of the respondents would have liked more education. This indicates that they experienced a need for more knowledge that they feel is missing, and that would have possibly benefited their work.

Designers' two major requirements for a method or tool seem to be that it must *(1) help them to fulfill specified requirements* on the prospective product, and at the same time *(2) reduce the risk that important moments in the product development process are forgotten*. Both are related to the third and most important requirement, that the use of the method or tool *(3) must reduce the total calendar time (from start to end) to solve the task*. For example, if the method or tool helps them to fulfill specified requirements, it will also most likely help them to reduce the calendar time as well as the number of working hours needed to accomplish the product development. Perhaps much would be gained if those three requirements were used as a first overall validation of the usefulness of the method or tool. If the result of the validation is positive, further requirements can be used in order to gain a more detailed validation.

A method or tool must *help to fulfill a specified requirement.* The question is, however, what to do if no requirements exist or if they are few and weak? Both Nutek (2002) and results from Paper V indicate that customers tend to state few

[25] The alternatives were found in the literature and during previous interview studies (see Lindahl (2001) and Papers III, V and IV.

environmental requirements. This implies that the designer has either no need or a low need to help to fulfill specified requirements, in this case Environmental-related requirements. This also implies that some of the identified requirements explain why the utilization of DfE methods and tools are low, and what could be done to increase the utilization.

Contribution to the thesis

A great part of this thesis is based on the results from this final appended paper, and therefore has a strong influence on the thesis in many ways. In fact, all of the results found in this paper are used in the thesis.

5 Discussion

One objective of this research has been to explore what basic requirements a method or tool ought to fulfill in order to become actively used by engineering designers. A second objective has been how to make DfE methods and tools more actively used in industry among engineering designers by applying these basic requirements. This was accomplished through the collection of empirical data from industry through the use of different data collection methods. In this chapter, the empirical data collected for this research are discussed.

5.1. Designers' comprehension and experience of utilized methods and tools

Product development can be described as a process with a number of activities, (preformed for example by designers), aimed to achieve a desired outcome. Methods and tools are used within this process to support the progress of the process. Product development is carried out in large variety of companies that differ in reference to their products, organization, culture and size; all of these differences affect what method or tool is most efficient and effective to use.

5.1.1. Why use methods and tools

One issue of interest during the studies (Papers III - VI) has been the way designers comprehend and interpret the terms "method" and "tool". For classification reasons, it has been of interest to understand if designers comprehend any difference between method and tool, and if so what the comprehended difference is. The outcomes from the research studies presented in Papers III - VI show that what one designer may consider as neither method nor tool is for another designer considered as a method, and perhaps for a third a tool and for a fourth both a method and a tool. The surveys show that from the perspective of the respondent, there were no experienced needs to distinguish between the two terms. The majority of the designers use the terms in parallel to each other, even though some of the designers felt there was only a small difference between the two terms. The conclusion from the studies is that designers do not tend to pay a great deal of attention to whether the meaning they use is defined as a method or as a tool. What is important for them are the benefits that they receive from the use of the method or tool. The author's conclusion is that whether a means (way of working) could be categorized as a method or tool is of less importance, and more an academic rather than practical concern. For the user, the more important issue is the result from using the method or tool, rather than whether or not it is denominated as such.

As shown in the research (Papers III - IV), designers feel that methods and tools are used to gain a more and more efficient product development process, and the means to do this is through better structure. However, the author does not interpret this primarily as the wish of designers to, for example, develop more products, increase quality, and/or save or increase the company's profit. Instead, the conclusion is that designers' main desire is to complete ongoing tasks and, for example, reach a higher degree of professional pride, and do so under less time pressure and in a more satisfactory way. This could be related to Norell's (1992) conclusion that a determining competitive factor in industrial product development is to have a fast and secured product development performed by fellow workers with high work motivation and a high sense of responsibility. Such high levels of motivation and responsibility are connected with professional pride, and the author's interpretation is that there most likely is a strong relation between the two. If designers have professional pride, they are also likely to be motivated and responsible. Further, the outcome from the designers' main purpose is often in line with the company's purpose, i.e. more developed products, increased quality and more money saved and even earned.

The qualitative research interviews (Papers III - V) have shown that designers' understand that their used methods and tools help them to reach their goals, and for three major reasons.

The first reason is that methods and tools ***facilitate various kinds of communication within the product development process*** (Papers III - V). This communication could support visualization of products and give shape to new ideas through, for example, drawings. Hovmark and Norell's (1994) GAPT model's highest level, "teambuilding in design work", also partly highlights this reason. These authors describe the benefits of the support of the use of methods and tools in order to achieve a common language among the product developers.

Another aspect of communication, also described by Cross (2000), is that the communication process itself facilitates the transfer of systematic work out of the designer's head and "onto the paper", as well as enhancing communication with other designers. The transfer of visualization on paper also implies that the designer's mind, to a higher degree, can focus on intuitive and imaginative thinking. This transfer and the importance of being able to focus on intuitive and imaginative thinking was also something directly highlighted during some of the interviews (Papers III - IV).

The second reason, and one interpreted as an important one from both a designer and company point-of-view, is that ***methods and tools function as knowledge and experience backups.*** By developing their own methods and tools based on personal experience and knowledge, or implementing existing methods and tools and modifying them to better fit into the company's context, knowledge and experience from the specific product development task are integrated into the methods and tools as a know-how backup. This is also in line with Cross's (2000) discussion on how some methods and tools are formalizations of informal techniques. Existing methods and tools are modified to fit the company-specific context, and company-specific techniques are formalized, for example in manuals and working procedures. In other words, knowledge and experience are built into the methods and tools. The author's interpretation, based on this research's studies (Papers III - V) as well as previous studies (Lindahl 2000; 2004), is that this *built-in know-how* of non-trivial data facilitates designers who change departments. In this case, their predecessors' experiences and knowledge are built into the methods and tools themselves. One example of this is checklists that are based on previous experience as shown in, for example, Ulrich and Eppinger (2000). The second reason could also be seen as a way for individual designers to build in their own knowledge and experience in order to facilitate future work; one example is making the method or tool more efficient by adding extra procedures that result in a more useful result.

The third related reason is that methods and tools may ***contribute with structure*** (Papers III - V), something also highlighted by Norell (1992). López-Mesa and Thompson (2002) state that methods and tools may bring rational structure into the product development. Structure, according to these authors, is something requested in a complex multi-objective product development environment in order to accomplish effective and efficient work. This structure also facilitates the ability of designers to change work tasks.

5.1.2. Frequency as an indication of utilized methods and tools

As shown by Norell (1992), methods and tools differ substantially in regards to their specific aim of use and structure. However, the existing lists of requirements that a method or tool ought to fulfill to become utilized – i.e. extracted from existing knowledge of use – implies that there also exists some common characteristics. The aim in the research studies has not been to try to compare or equate different methods and tools, but rather to identify the common characteristics of these methods and tools, and subsequently use these characteristics to develop requirements for them. Consequently, the focus has not been to identify as many methods and tools as possible, but instead to identify those that are actually utilized, and to find out to what degree (total working hours) that they are used by designers.

The studies reveal that designers view themselves as users of methods and tools in quite low numbers (Papers III - V), which the analysis of the results from the questionnaire emphasize (Paper VI). The most utilized tools are various kinds of Computer-Aided Design (CAD) tools, for example Pro Engineer, Catia, SolidWorks and AutoCad. Some of the designers use two or more CAD tools (Paper VI). If all Computer-Aided Design (CAD) tools count as one tool, then there exist few additional methods and tools utilized independently by more than a fifth of the respondents (see Table 3 of Paper VI). The research result that few methods and tools are used within industry is in line with results reported by Cantamessa (1999) and Janhager *et al.* (2002).

Table 3. Methods or tools mentioned in Paper VI. The number before the brackets in the table indicates the number of respondents that have answered that they use a specific method or tool. The number within the brackets denotes the percent of all respondents. N=175 respondents)

Name	CAD tool	Number of users among the respondents (% of respondents)
Brainstorming		131 (75%)
FMEA – Failure Mode Effect Analysis		90 (51%)
FEM – Finite Element Method		71 (41%)
Pro Engineer	CAD	61 (35%)
LCC – Life Cycle Costing		49 (28%)
Design for Assembly		46 (26%)
Catia –	CAD	40 (23%)
EEA – Environmental Effect Analysis / E-FMEA – Environmental-FMEA[26,27]		37 (21%)
LCA – Life Cycle Assessment		31 (18%)
QfD – Quality Function Deployment		31 (18%)
FTA – Failure Tree Analysis		16 (9%)
SolidWorks	CAD	16 (9%)
AutoCAD	CAD	15 (9%)
Fishbone (Ishikawa) diagram		15 (9%)

The designers' understanding concerning their own individually most utilized methods or tools was positive (Papers III, IV and VI). The designers were quite satisfied with the degree the method or tool fulfilled their experienced needs. It should be noted that the most generally used methods are selected by the individual designer or together with the nearest design colleagues, which may have influenced these positive attitudes. In general, the designers who participated in the studies were very convinced that the use of their individually most utilized method or tool contributed to making the final product better (Papers III, IV and VI); only a fraction did not believe that their use contributed in some way (Paper VI).

How valuable are these results and how can they be used? It is important to note that it is inappropriate to draw conclusions about a method or tool's usefulness based solely on if it is used in great numbers or is frequently utilized or not. Just because a method or tool is not frequently used does not necessarily mean that it is an inappropriate method or tool. On the contrary, it may be perfectly suited with a high degree of usability for the specific user or purpose, and may even exceed the user's stated demands. A method or tool used by few designers and with a low degree of utilization may imply that the method is efficient, e.g. when a method or tool requires fewer people involved and if the appropriate outcome is gained with few working hours. Even so, it is still relevant to find out which methods and tools

[26] Environmental-FMEA is a parallel used name for Environmental Effect Analysis.

[27] The author has further developed the EEA method (Lindahl 2000). The author stresses that he has done everything not to influence the respondents about this fact, and that there is no reason to believe that the respondents have been aware of this fact.

are utilized the most. The degree of utilization may still indicate what types of methods and tools are needed, as well as what general features they have that may influence the utilization. The studies carried out for this research have shown that if a method or tool is utilized, it is often also quite regularly utilized. SMEs do not use methods and tools to a lesser degree than major companies do, nor has the education level a significant influence on the method or tool's utilization.

5.1.3. Utilization of a formal product development model

Product development models have, in general, an influence on the utilization of other methods and tools. The product development model tends to more or less define, for example, which, when, who and how to use different methods and tools during the product development phase.

The studies presented in Papers III - VI show a high preference for a defined product development model. Respondents in large companies use a defined product development model to a slightly higher degree – approximately 88% in comparison with 65% for the respondents in SMEs (Paper VI). This result can be related to the Janhager *et al.* (2002) study within Swedish industry, which showed that 61% of the companies investigated had a formal product development model. In addition, a study of UK industry carried out in order to determine the level of utilization of methods during the product development phase reported a similar result (Araujo *et al.* 1996). According to that study, 69% of the British companies employed a formal product development model. This implies that the numbers received are above – but still in line – with other studies.

Even though a formal product development model exists at a company, the existence is more or less irrelevant unless it is utilized and known by the presumptive users, in this case designers. One of the studies shows that those designers that claimed to utilize a method or tool by the company defined product development model (Paper VI) utilized it, on average, in approximately 70% of the product development projects. This is quite a high degree of utilization, especially when considering that the remaining 30% may imply a partial utilization of the product development model. Janhager *et al.* (2002) reported a much lower degree of utilization, with 51% responding that the procedure is followed in all projects, while the remaining respondents stated that the procedure was utilized in only some projects. Even though the numbers differ, there seems to be a quite regular utilization of product development models.

In order to find contextual differences, the investigation included whether the size of the company or the department size influenced the degree of method and tool utilization. Based on the studies' empirical material, it is not possible to find any significant influence on the utilization of methods and tools (Papers III - VI). However, the differences found between the answers from respondents from small and major companies may be because of their different needs or awareness of the benefits[28] of having a formalized product development model. Janhager *et al.* (2002) show that the size of the companies (in number of employees) seems to re-

[28] These benefits include everyone getting an overview of why, when, who and how to utilize different methods and tools, as well as how to utilize the outcome.

late to the existence of a defined product development model. In other words, the larger the company, the greater the number of different professional categories involved in the product development, and the more likely a defined product development model will exist. More people naturally imply more interactions, and thus a greater need for formal strategic planning and communication for carrying out product development in an efficient and effective way.

The results show that the existence of a product development process influences the utilization of methods and tools. It is, however, not possible to make any conclusions about the degree of that influence.

5.1.4. Collaboration and freedom of the utilization of methods and tools

Modern product development involves increasingly more teamwork as well as incorporating more and more people. This development is caused, for example, by an increased technical complexity in products and an increased time pressure, as discussed in Beskow (2000) and Wheelwright and Clark (1992). Wheelwright and Clark (1992) and Cooper *et al.* (1998) have emphasized an increased need and importance for multifunctional teams and similar types of interdisciplinary collaboration in order to minimize missed communication, provide a broader knowledge base and increase the cross-fertilization of ideas[29].

Designers' degree of collaboration and freedom to select methods and tools has emerged during the research to be quite an important issue (see Papers III - VI). The increased level of collaboration creates demands for increased coordination between different actors working with product development. This increased coordination will also have more or less influence on designers' freedom to utilize their methods and tools.

All four studies show that designers view themselves as being free to decide ***when, how,*** with ***whom*** and ***what*** they want to do in order to accomplish their tasks (Papers III - VI). Even though other designers and staff from other departments are involved in the utilization, the individual designer still performs most of the practical method and tool utilization. For methods and tools based on simultaneous collaboration, for example brainstorming, the need of coordinating meetings reduces designers' freedom, especially if many people are involved in the use. The coordination problem to get the needed actors (designers) together and enable time for start up and setup increases when using these types of methods and tools too frequently. This implies that even though designers like collaboration, they do not favor methods and tools that require excessive simultaneous collaboration (Papers III and IV). Simultaneous collaboration is collaboration where designers must come together at the same time and location in order to utilize the method or tool.

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[29] Related to the earlier discussion about the importance of communication, the perspective could be switched so that interdisciplinary collaboration could be seen as a means to minimize missed communication, provide a broader knowledge base and increase the cross-fertilization of ideas.

Designers feel like they have great freedom to decide which methods and tools to utilize, a conclusion also drawn by Janhager *et al.* (2002). However, even though designers experience great freedom to select methods and tools, it is questionable how big this freedom really is; in actuality, their freedom is restricted because of the need for collaboration. This collaboration is quite dependent on what other designers and users, for example managers, do and decide, i.e. what methods and tools they prefer.

The conclusion, primarily based on the studies (Papers III - VI) but also on existing research by Norell (1992; 1993) and Beskow (2000), is that an actor's method and tool use is a result of their work effort in using the method or tool, as well as the degree of influence on the collaborative pattern in utilizing a method or tool, as shown in Figure 7. This is also in line with Janhager's discussion about different types of users (2002). For example, some actors, such as a manager, may have a high degree of influence on the utilization of FEM, but a low degree of work effort (see alternative "D" in Figure 7). At the same time, a designer may have a great work effort but low influence on which CAD tools are used (alternative "A" in Figure 7).

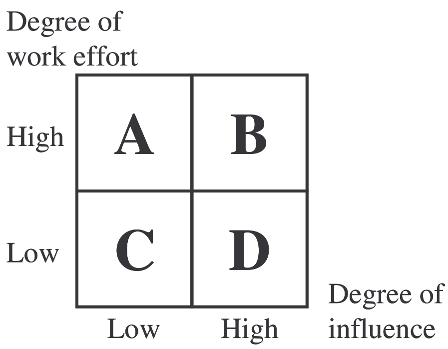

Figure 7. An actor's method and tool use is a result of their work effort in using the method or tool and the degree of influence on the collaborative pattern in utilizing a method or tool.

The conclusion based on the discussion above about designers' collaboration and freedom of utilization of methods and tools is that designers, especially when having a high degree of influence on the utilized method or tool, have an important role in the implementation of new methods and tools.

5.1.5. Reflection and education over utilized methods and tools

Even if designers have access to presumptive methods and tools, and have the freedom to select which ones to utilize, it may not necessarily be enough to get such methods and tools utilized. The presumptive user, in these studies the designer, must also be familiar with the method or tool's existence. One way to gain awareness is through education. Another way is through continuous reflection of how methods and tools can be used to contribute to their own work, and how they can be improved. This, in combination with education of the staff, is necessary in order to maintain the company's competitiveness (Beskow 2000). According to Beskow (2000), education should begin with general information about what context the method or tool should be used in, why it should be used, and also the background behind the methodology. Following this, more specific information about the method or tool and how to use it should be presented. Learning should be seen as a lifelong process, and an important element in the learning process is reflection (Schön 1990).

Reflection

The experience among the designers in the studies was that they had limited time for reflection on their work due to their everyday work activities (Papers III - VI), implying that time available for reflection on the usefulness of methods and tools is limited.

Reflection can also take the form of more formal follow-up of, for example, utilized methods and tools. However, the conclusion is that a vast majority of designers in the studies did not know whether there was any formal follow-up or not (Papers III - VI). In fact, only one out of ten of the designers in the study presented in Paper VI were aware that there was a follow-up. At the same time, three out of ten designers stated that there was no follow-up of unsuccessful method and tool use (Paper VI). The studies show that the low degree of follow-up is independent of the size of the company (Papers III - VI). In addition, when designers were asked about the degree of formal follow-up for their most utilized methods or tools, they replied that the follow-up was low. Altogether, this implies that reflection upon one's own work and utilized methods and tools was low and vague. Even if a follow-up existed, a large number of those studied were unaware of this.

Education

As the results show, few designers have received more than five days education on the method or tool used most (Paper VI and Åkermark and Lindahl (2003)). Also interesting for this research was that one-fourth did not receive any education at all, and only one in ten had received more than two weeks of education (Paper VI). The designers, however, were quite satisfied and appreciative of the method and tool education they did receive (Paper VI). The fact that these designers were satisfied with their education does not imply that they are satisfied with the amount of education; in fact, several of the designers in the studies wanted more education (Paper VI). One thing mentioned during some of the interviews (Papers III and IV) was that some designers experienced a need for more knowledge in order to obtain a better understanding of how to use methods and tools more efficiently and effectively.

Knowing that the respondents have stated that the method or tool they use the most is used in 68% of all product development projects, and that they would like more education, it is interesting that so little emphasis seems to be placed on education (see Paper VI). What if more education could make the designers more familiar with the method or tool's refinements? If this results in time savings, it would be an investment that could have quite a short pay-off time.

One reason for the limited focus on education and reflection may be time pressure, a factor expressed by the designers in the questionnaire studies (Papers III and IV) and by Stalk and Hout (1990). It is this time pressure that accounts for time losses in, for example, education (see Beskow (2000)) and reflection.

5.1.6. Implications of a low degree of follow-up and education

The presence of follow-up is not especially significant, unless it is related to what its absence may imply – in this case, for the designers and the company as a whole. The low degree of follow-up, for example the very low or nonexistent incidence of methodical follow-up of utilized methods and tools, and especially of less successful utilization, are surprising in some respects but not in others. It is surprising due to the risks that this lack of follow-up may result in, but at the same time not surprising due to the author's experience from interviews with designers (Papers III - V) and what has already been highlighted by Andreasen (2001) and Janhager *et al.* (2002).

From both method and tool developers' as well as a managers' point-of-view, the low degree of follow-up should be a highly relevant issue due to the problems that this may cause. The presumptive risk is that managers may make faulty decisions concerning the utilization of methods and tools. The interpretation of the answers from the respondents in the studies indicates a gap between management's image of the utilization of methods and tools, and the real utilization among the respondents.

When a new method or tool is implemented, the utilization increases during an education process and, in general, decreases thereafter over time. This depends on how the respondents experience the utilization of the method or tool (Norell 1992). The author's experience is that the managers tend to give a more positive image of the utilization than that given by the designers. However, this does not mean that the managers intend to give misleading information; they just seem to be less aware of the real utilization of the methods and tools and the user's, i.e. designer's, benefits from the methods and tools. The low follow-up rate implies a risk that management, instead of discarding a method or tool that is not useful, will introduce additional, similar methods and tools.

The result from the respondents implies that when implementing a new method or tool, an old one must be abandoned or changed. It is impossible to continue to add new ones[30]. The respondents cannot handle too many different methods and tools. However, even when the method or tool itself is abandoned and replaced by new ones, the positive features of the method or tool are, according to the respondents, adopted and utilized. This implies that the memory of the method or tool lingers on, and is integrated by the designer into the new methods or tools.

[30] See method and tool requirements.

5.2. Obstacles for increased method and tool utilization

Designers in the studies (Papers III - VI) experienced a strong need for more methods and tools; however, the stated need for DfE methods and tools in particular was not high (Paper V). It is sometimes claimed that the industrial utilization of methods and tools is low, and that a higher degree of utilization would be fruitful. However, this statement should not be misunderstood and interpreted as a need for industry or designers to utilize a larger number of methods and tools. The number of utilized methods and tools is of less importance; what matters more is instead how to use the suitable method or tool for the actual context instead of working ad-hoc. This interpretation is in line with the research of López-Mesa *et al.* (2002).

An interesting image appears when considering the needs for utilization (see Section 5.1.1) with the current utilization (earlier described in this section) of methods and tools and the obstacles[31] to the utilization of more methods and tools rated in one of the studies (Paper VI). At the same time, as designers felt great freedom and wanted to utilize more methods and tools, three quarters of the designers in the study presented in Paper VI were kept back due to time limitations. Time limitation is mentioned almost twice as often as the second reason, that concerning expenses for purchasing. Two of the other obstacles, lack of education and lack of knowledge, relate to both the time obstacle but also to the fourth obstacle concerning management.

All of the four highest-ranked obstacles in the study presented in Paper VI – lack of time, expenses for purchase, education and knowledge – can be related to the management obstacle. Management is the one who allocates resources and manages the work. If management is uninterested in an issue, it is most likely that it will not allocate money and time to solve the obstacles. This is truly a conflict, even though the designers experience great freedom and those different obstacles restrict them.

Factors such as *"lack of adjustment to the needs of practitioners"* that could explain the low number of used methods and tools as well as their low utilization have been discussed by Frost (1999) and Stempfle and Badke-Schaub (2002). Some of the factors expressed by the respondents during the studies presented in Papers III - V were, for example, the skepticism against the whole idea of methods and tools, also described by Cross (1997). Some respondents felt that methods and tools limited their creative freedom (Paper IV). Respondents also expressed their view that methods and tools are sometimes too systematic or over formalized to fit into the often rather messy and continuously inconsistent context, something also stated by Ernzer *et al.* (2002). This is especially true when the designer (user) understands the context, and realizes what methodological steps could be excluded or changed[32]. This is, in relation to Cross' (2000) discussion about formalizations of informal techniques, perhaps a natural reaction (see also Stempfle and Badke-Schaub

[31] Examples include lack of time, expenses of purchasing, expenses for education, demands from customers, and lack of motivation.

[32] This relates to Stempfle and Badke-Schaub's (2002) statement about theory building (see section 2.2.3).

(2002)). The formalization and generalization of an informal technique in order to get a more general field of application also implies a reduction of the customization in order to fit in more contexts[33].

When summarizing designers' comprehension of their obstacles for the current utilization of methods and tools, the conclusion is that designers' utilization of methods and tools depends on three major factors (Papers III - VI):

- **The methods or tool's experienced degree of usefulness –** If, for example, the designer is under time pressure and the outcome from the method or tool is not vitally important (the outcomes appropriateness is low), it is likely that the method or tool will not be utilized. Instead, there is a utilization of previous experience to solve the task. Related to this is also the method's level of usability. The degree of utilization will be low if the method or tool is unnecessarily complicated, for example if it requires excessive start-up time or education in relation to the outcome. One of the examples given about this during the interviews (Paper IV) is when it is possible to obtain the desired outcome through a rough calculation by using a pen and a paper instead of using an advanced calculation program.
- **Requirements from the customer[34] –** If the customer requires the utilization of a specific method or tool or a specific product development task can be solved by a certain method or tool, then this method or tool will be utilized. In this case, both the degree of usability and appropriateness for the designer is considered as low, but the degree of appropriateness from a company point-of-view is high. Without any plain pressure from the customers, it is hard to make companies and consequently designers motivated to increase the use of, for example, DfE methods or tools. The motivation power also relates to the freedom of action the company and its designers have to change the products into a more environmentally friendly product. If they do not have this freedom, it is less likely they will use any DfE method or tool.
- **Primary purpose to utilize the method or tool –** If the method or tool covers an issue with regular occurrence and represents a major part of the daily work, it is more likely that it is regularly utilized. This is the case even though the degree of usability is low because of a high need for initial education.

[33] It is like a pair of trousers made to fit almost everyone, but in reality fit almost no one perfectly. The more it ought to fit, the less it will perfectly fit, at least without any modifications, such as, for example, shortening.

[34] A customer is, in this context, limited to include only professional customers.

In addition to the factors above, still others have been identified that are even more DfE-related[35]:

- **Lack of education/knowledge about DfE –** One reason for the lack of stated needs of and the motivation to use DfE methods and tools is a lack of knowledge within the area of DfE (Paper V). This lack of knowledge includes that they do not know the advantages of using DfE methods and tools, and that they do not know the existence of several conceivable DfE methods and tools.
- **Obstacles with integration –** Environmental issues, along with DfE methods and tools, are often utilized without any connection to the ordinary product development (Papers II and V). This is, in many cases, a result of the historical fact that departments other than the design departments, for example the environmental or quality departments, have managed the environmental issue, and in many cases still do so. The environmental issue has not been fully integrated into the ordinary product development, and has, in many cases, been treated by designers as an extra burden. Another problem pointed out by Lenox and Ehrenfeld (1995) is that DfE methods and tools tend to focus on the single objective of minimizing environmental impact. The treatment of the environmental issue with no relation to other aspects is also an obstacle for integration with the ordinary product development (Lindahl 2000).
- **Expenses –** All the obstacles above, more or less, relate to the obstacle of expense. DfE is still often treated as a cost instead of as an investment for future gains. In many cases, this is based on historical reasons, when environmental issues were equal with costs for purification of emissions. However, there is no automatic connection between environmental improvements and costs resulting in a higher price on the product or a reduced profit. The very core of product development is to optimize the product; in the case of DfE, this is from an environmental point of view. The problem occurs when this is done in isolation to other aspects, for example economy. This may result in, from an economic point of view, cost-inefficient products.

5.3. Designers' method and tool requirements

This section's starting point is a discussion about requirements and so-called context-related requirements[36]. The latter parts relate to empirical results.

5.3.1. Implications of vaguely-defined method and tool requirements

Requirements for methods and tools found in the literature are, for the most part, too vague and general (Papers I and II) to be utilized when developing new methods and tools, a conclusion also supported by Ernzer and Birkhofer (2002). Many requirements may appear to be clear and simple, but when trying to interpret and use

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[35] Of course, some of the obstacles below are relevant as an explanation for the low utilization of other types of methods and tools as well.

[36] In Paper I named as "criteria".

them, problems invariably occur. One often-mentioned requirement is that a method ought to be *"easy to learn, understand and use"*. The meaning of the requirement could be interpreted in many ways depending on the person's preferences behind the interpretation. To be useful, a requirement must be more specific and precise. This implies that the unanswered question is more specifically how a method or tool should be easy to learn, understand and use.

When making a mapping and inter-relational study of two commonly mentioned requirements (Paper II) for a method or tool *"easy to learn, understand and use"* and *"time efficient"*, as Figure 8 illustrates, a more complex image appears. Similar mapping and interrelation studies were conducted for several of the most commonly mentioned requirements, as described in Section 2.3.1. The vague requirements imply a risk for misconceptions and failure in the use of those requirements. They also imply a risk that the method and tool developers may believe that they have fulfilled what they interpreted as designers' requirements, when in reality they have not done that at all.

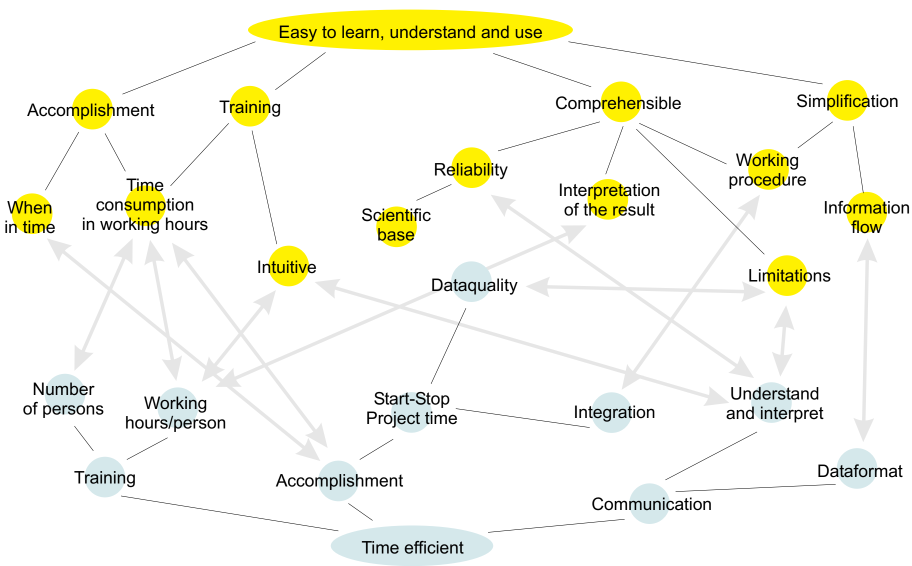

Figure 8. An example of a mapping and interrelation study of two commonly mentioned requirements (Paper II) for a method or tool: "easy to learn, understand and use" and "time efficient".

5.3.2. Context aspects on method and tool requirements

Klein (1994) states that a democratic or participative method or tool needs to include what is important to the people in the situation, even if this does not match the original purpose defined by the method or tool developer. The author's conclusion, based on the previous discussion presented in this thesis, is that it is important to understand the context in which a method or a tool is used in order to state requirements on the method or tool. Based on studies by Norell (1992; 1993), Klein

(1994), Ehrenfeld and Lenox (1997), Beskow (2000), Ritzén (2000) and Ernzer and Birkhofer (2002), the conclusion is further strengthened. The research has highlighted that this understanding of the context in which designers use methods and tools seems to be an important issue.

The above conclusion, especially considering Klein (1994), implies that DfE methods and tools must not only be appropriate from an environmental perspective, but from a user perspective as well. Further, if a method or tool is developed and applied without understanding the circumstances in which it was developed and without a diagnostic approach to the circumstances in which it is to be applied, in the likely result will be inappropriate application (see Thoben *et al.* (1997)).

The discussion above implies that whether a method or tool is actively used or not does not only depend on the method or tool itself. As shown in the studies, a method or tool can be actively used in one context but not in another (Papers III - VI), something which is also supported by Ernzer and Birkhofer (2002). When a method or tool is selected and later implemented, several context-related aspects, for example organizing arrangements, social factors, physical settings, visions, and technology, influence their active use as well as the existing context. Nutek's (2003) conclusion is in line with this, as they state that the company's size, branch, operations and even the expertise that exists within the company are all important to the best-suited choice of method and tool. Change in one factor will usually require complementary changes in another. This implies that the interdependence between organizational characteristics must be taken into account.

5.3.3. Discussion about identified method and tool requirements

Despite the lack of identified formal requirements (Papers III - VI), the designers had several informal requirements, often connected with the reasons expressed for utilizing methods and tools. This section presents and discusses the method and tool requirements identified from this research (Papers I - VI), several of which are interlinked.

Appropriateness-related requirement

Reliable and relevant outcome – One of the most important requirements is that a method or tool must provide outcomes that are relevant and reliable for the user, in this case the designer. The requirement itself is problematic depending on the problem described, especially when considering how to quantify what an appropriate outcome is. In other words, what for one designer may be considered a reliable and relevant outcome, may not be for another. For DFE methods and tools, where are often problems in finding adequate data, the issue of reliable and relevant outcomes becomes even more difficult since much of the used data is instead based on validations, assumptions and limitations. The capacity to validate whether an outcome is reliable and relevant is dependent on the user's experience and knowledge. As shown in the studies, designers' knowledge about DfE-related issues – i.e. their capacity to validate the outcome – appears to be low (Papers III - VI).

Usability-related requirements

Direction towards a target area rather than a road map to the target – This requirement relates to the method or tool's degree of usability, i.e. efficiency and effectiveness. "Freedom of action" appears, at least according to this research (Papers III - VI), to be important for the designers. It also seems probable that this is the very nature of the product development, often called the design paradox (Ullman 1997). Another element of the nature of product development is that the image of the goal changes as the project progresses. Consequently, this requirement is primarily relevant for methods and tools used in the early phases of product development, when methods and tools are applied in order to get a direction for further work, for example to get an indication of whether the proposed concept is working or not. This is in contrast to the latter stages, where a more concrete and precise result is required in order to, for example, optimize the product. Methods and tools should not be too prescriptive, and they should allow the user to bypass steps depending on what the method or tool is being used for.

Designing is a creative process as well as a trade-off situation – on one hand, the designers interviewed for this research wanted structure, and on the other hand, they wanted freedom to act more independently (Papers III - V). There may be a risk, however, that a method or tool that maps out a specific route may "lock" the designers in a specific path, thereby jeopardizing and diminishing the freedom for innovation.

Time efficient – This is not only one of the most frequently mentioned requirements during the studies (Papers III - VI), but is also in the literature a more or less explicitly mentioned requirement. The requirement could be interpreted as a logical consequence of increased competition (Stalk and Hout 1990) and the design paradox (see section 2.1.2). The requirement is related to the degree of usability, i.e. to "do things right" and to "do the right things" (see Section 1.4). However, as described earlier in section 5.3.1 the interpretation of the requirements is not so obvious. This is due to the fact that these requirements can imply different things, but at the same time be experienced subjectively by different persons, i.e. what is time-efficient and in comparison to what?

Setup time – Related to the time efficiency is the conclusion based on the studies (Papers III - V) that a method or tool must not have an excessive setup time. For designer comprehension, complicated methods and tools must be daily or at least regularly utilized; otherwise, designers tend to forget how to utilize the method or tool's specific functions and the setup time increases[37]. At the same time, this implies that the number of methods and tools a designer can utilize is limited.

Not require excessive simultaneous collaboration – Based on the discussion in Section 5.1.4, the conclusion is that a method or tool must not require too high a degree of simultaneous collaboration.

Integration – Adjustable to different contexts – Mentioned more or less explicitly by some designers during the studies (Papers III - V) is the different companies' culture or specific ways of performing tasks, often a fundamental reason for the

[37] For further discussion, see Paper IV.

success of a successful company. This implies, as previously discussed, that a method or tool must be able to fit into and be adjustable to this culture, i.e. the specific context, an assertion also supported by Ernzer and Birkhofer (2002). Otherwise, as mentioned explicitly by one designer with extensive experience from many different companies, there is a risk that the method or tool will destroy the culture and the company's winning concept. Further, if the method or tool is not sufficiently integrated or adjusted into a company's context, there is also a risk for stand-alone methods and tools as described by Ehrenfeld and Lenox (1997), i.e. methods and tools with outcomes not appropriate to designers. During the studies, respondents expressed several examples of stand-alone methods and tools (Papers III - V).

Computer based – When looking at which methods and tools are used more regularly, the conclusion based on the studies (Papers III - VI) and other existing research studies such as Norell (1993) and Janhager *et al.* (2002), is that the method or tool should be computer-based.

Easy to adopt and implement – This can be seen as an overarching requirement that can be divided into sub-requirements:

- **Gradually introduced gadgets/functions –** A method or tool must not be experienced as being too complex/complicated, at least not from the beginning (see Reich *et al.* (1997). This implies that the user should not be required to know everything and understand the method or tool's functions from the beginning to be able to use them. When the user gains experience, he or she can add more and more gadgets/functions to, for example, make the result more and more precise. According to many of the respondents in the studies, too many methods and tools attempt to accomplish too much from the beginning instead of starting on a lower level (Papers III - V). According to some of the designers in the studies, it is better to have many different methods or tools that complement each other rather than one that tries to cover everything, especially when only a part of the method or tool is used (Papers III - V).
- **Easy to understand the benefits –** Simplicity also requires that it must be easy to understand and experience the benefits of the method or tool (Papers III - V), something which is in line with Norell (1992). According to the studies, the method or tool must be intuitive, logical and easy to communicate, and the benefits received by applying the method or tool must be obvious in comparison to the effort that would be needed if the method or tool was not used (Papers III - V). This requirement is especially important for rarely used methods and tools. The lack of fulfillment of this requirement has been highlighted by Cantamessa (1997).
- **Intuitive and logical –** The presumptive user ought to be able to realize how the method or tool and its different parts fit together. Designers in the studies understand that it is advantageous if the method or tool is intuitive and resembles other methods or tools that have been used (Papers III - V). This may provide benefits such as a faster learning process and easier integration of different methods and tools. For example, if the designers are already familiar with FMEA, this seems to aid the learning and intuitive understanding of the methodically-similar EEA method (Lindahl 2000). On the other hand, if the de-

signer must read several hundred pages of a long description or manual (often with academic jargon) before even using the method or tool, it is likely that he or she never will even start reading. Instead, designers in the studies (Papers III - V) preferred methods and tools requiring a minimum of education, and which they could start up and use immediately. After that, if questions occur, they should know where to find answers, for example from a manual. The conclusion is that the intuitive and logical aspect is especially important for methods and tools that are rarely used.

5.3.4. Ranking and categorizing designers' method and tool requirements

In order to obtain a deeper understanding of the requirements that a method or tool must fulfill in order to be successfully utilized, the literature studies (Papers I and II) and the result from the interview studies (Papers III - V) formed the basis for the third study (Paper VI). The results are presented in Table 4, beginning with the highest-ranking requirements (Paper VI).

The increasing competitive environment forces companies to improve product development efficiency (Beskow 2000). According to Smith and Reinertsen (1997), improvement activities often share four key product development objectives, namely to improve: 1) development time (speed), 2) product cost, 3) product performance and 4) development cost. Product development teams attempt to manage the six potential interactions between those key objectives (see Figure 9). It is important to understand that these potential interactions between any two internal factors depend on the characteristics of the specific product context (Ulrich and Eppinger 2000). In many cases, the interactions are trade-offs; a prime example is how decreasing the product development time may lead to an increased development cost. The majority of the requirements a method or tool should fulfill in order to be utilized by designers can be related and sorted to the improvement objectives described by Smith and Reinertsen (1997). In Figure 9, the author has made this connection. When doing this, the starting point has been to find the closest connection between the requirement and the four prioritized need areas described by Smith and Reinertsen. For some of the requirements, it has not been possible to find any relevant connections.

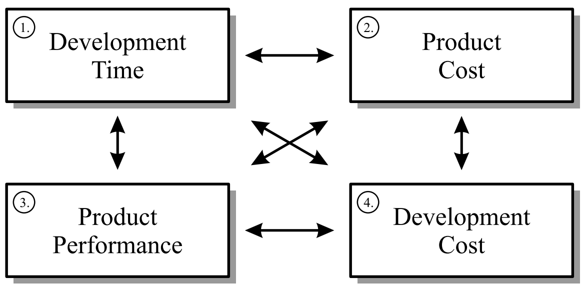

Figure 9. Different kinds of reasons for using a method (Smith and Reinertsen 1997).

Table 4. The different requirements sorted in relation to their importance (R) in making a method or tool utilized, as validated by the responding designers. (The different requirements have been valid on a scale from 1 = not important to 9 = important). The table also shows the connection between different requirements that make a method or tool utilized and the key objectives for improvement activities in the product development process (C) described by Smith and Reinertsen (1997) (1 = Development Time, 2 = Product Cost, 3 = Product Performance, 4 = Development Cost). Total (N) and (n) = 187 respondents.

R	Requirements	Method	Tool	C
1	Helps me to fulfill specified requirements on the prospective product	7,46	7,36	3
2	Reduces the risk that important moments are forgotten	7,31	6,58	3
3	Reduces the total calendar time (from start to end) to solve a task	7,23	7,12	1
4	Reduces the number of working hours needed to solve a task	7,02	7,27	1
5	Facilitates the cooperation between different colleagues	7,01	7,05	-
6	Reduces the cost for a product development project	6,98	6,93	4
7	Facilitates the management of a product development project	6,93	6,51	4
8	Generates results that are spontaneously experienced as reliable	6,72	6,71	1
9	Gives guidance/direction for further work	6,68	6,35	1
10	Generates an easily interpreted answer	6,68	6,73	1
11	Facilitates internal communication of data and results within a product development project	6,66	6,68	4
12	Is not experienced as unnecessarily complicated	6,56	6,51	1
13	Doesn’t have a high introduction threshold that must be overcome	6,53	6,47	1
14	Facilitates the evaluation of data in a product development project	6,48	6,52	1
15	Facilitates the data collection in a product development project	6,35	6,42	1
16	Must be capable of being used in the earlier phases of the product development process.	6,32	6,14	1
17	Doesn’t require a long education	6,30	6,27	1
18	Its limitations and shortcomings are easy to see and understand	6,26	6,26	1
19	Is intuitive	6,17	6,39	1
20	Provides quantitative answers	6,01	6,16	-
21	Can be integrated with other methods/tools	6,01	6,39	4
22	Facilitates external communication of data and	5,99	6,18	4

R	Requirements	Method	Tool	C
	results outside the product development project			
23	Is based on well-documented scientific grounds	5,84	5,86	-
24	Reduces the number of people needed to accomplish a product development project	5,79	5,84	4
25	Facilitates introduction of new employees	5,66	5,54	4
26	Provides an exact answer/direction for further work	5,61	5,77	1
27	Allows some of its parts to be skipped during the process, still providing useful answers	5,43	5,43	1
28	Can be transformed into a computer program.	5,37	6,11	-
29	Is transparent, i.e. an outsider can understand how the result has emerged	5,36	5,27	4
30	Doesn't require quantitative data	5,16	4,93	1
31	The customer demands its use	4,58	4,55	-
32	Is used by competitors	2,57	2,55	-

The highest ranked requirement is that a method or tool must help the designer to fulfill specified requirements for the prospective product that relate to the product's performance. The fact that this requirement is top ranked seems quite natural. According to Pugh (1991), a designer's main job is to balance all demands that exist on a forthcoming product in order to develop an optimal balance and thus a successful product.

The third highest-ranking requirement is primarily related to the objective of reducing development time (increasing efficiency). None of the requirements is clearly directly related to the product cost.

5.4. Method and tool requirements' implications on DfE methods and tools

The focus of this thesis has been on DfE and how to increase designers' use of DfE methods and tools. If methods and tools are to become actively used[38] in the product development process, it is important to increase the understanding about what make users consider them as usable and appropriate. Whether a method or tool has a specific environmental degree of appropriateness is more or less irrelevant unless it is not utilized.

The studies (Papers III - VI) have generated several requirements that can be adopted for the further development of DfE methods and tools. However, the surveys also indicate that the reasons for the low utilization of DfE methods and tools may also be related to the need for DfE methods and tools. As stated earlier, a method or tool must *help to fulfill specified requirements*. What, however, if no requirements exist or if they are few or weak as described in Paper V? Both Nutek

[38] The opposite would imply that there were no need in the first place to develop something neither needed nor asked for.

(2002) and the study presented in Paper V indicate that customers tend to state few product-related environmental requirements. This implies that the designers have no or a low need for help to fulfill, in this case, environmental requirements. This implies that some of the identified requirements can be used to explain why the utilization of DfE methods and tools are low, as well as what could be done to increase the active utilization of them.

Among DfE related-methods and tools, the only ones mentioned during the studies have been EEA and LCA (Papers III - VI). In the study presented in Paper VI, EEA was used by respondents from the majority of the companies, but LCA appeared to be used at very few companies. Aside from two exceptions, the respondents that used LCA were all working at major companies, with half of the respondents that used LCA working at the same company. It is interesting to note that EEA was so widespread among so many different companies. It seemed more probable that LCA would be more common among the companies, due to the major focus on that method in Sweden and the fact that the method is older than the EEA method.

Based on the research (Papers III - VI), it was not possible to conclude whether this is a result based on the fact that EEA was developed based on lessons learned from the use of other DfE methods and tools, i.e. designer requirements on a method or tool (see Paper II). Nevertheless, it has most likely had some influence.

6 Conclusions

The objectives of this thesis were *to identify basic design-related requirements that a method or tool should fulfill in order to become actively used by engineering designers*. Further to, *investigate how those basic requirements could be used to make DfE methods and tools more actively used in industry among engineering designers*. In this final chapter, the research questions are answered.

6.1. How designers experience their utilized methods and tools

This thesis contributes with new empirical data and analysis on how designers experience their utilized methods and tools, as well as what contributes to their utilization. Designers are in general satisfied with their utilized methods and tools, and this satisfaction includes their comprehended usefulness of the outcome from their most utilized method or tool. Despite this, one finding is that a low degree of follow-up implies a risk that methods and tools are used that affect the work within the company in a negative way. One example is when a manager receives false indications about how a method or tool fulfills its intended aim. Therefore, the conclusion is that there is a need for an improved follow-up regarding both the utilization and usefulness of methods and tools. The fact that requirements for methods and tools are very vague and hidden for the primary users makes it hard for designers to respond to managers regarding whether the methods or tools fulfill the stated requirements. The designers' experienced low interest from management for follow-up, in combination with the designers' lack of time, implies that it is very unlikely that designers will react and object, unless there are major problems with the methods and tools used. The conclusion is that in order to be able to better follow-up methods and tools regarding both their utilization and usefulness, there is a need for a better definition of requirements for methods and tools.

Another finding is that designers in general have three main purposes for utilizing methods and tools, of which the last two could be seen as parts of the first one. The purposes are to: (1) facilitate various kinds of communication within the product development process; (2) integrate knowledge and experience into the methods and tools as a know-how backup; and (3) contribute with structure in the product development.

Designers view themselves to be very independent in deciding ***when, how,*** with ***who*** and ***what*** method or tool they want utilize in order to accomplish their tasks.

Despite being satisfied with the method and tool education, designers would like more methods and tools as well as more education and time for reflection on their method and tool utilization. The current low degree of method and tool follow-up implies a considerable risk that management, instead of discarding a method or tool that is not useful, will instead introduce additional unsuitable methods and tools.

6.2. Obstacles for increased method and tool use among designers

The conclusion is that designers' utilization of methods and tools depends on three major factors that are negations of the major obstacles for increased method and tool use among designers:

- The method or tool's experienced degree of usefulness
- Requirements from the customer[39]
- Primary purpose to utilize the method or tool

One major obstacle for an increased level of DfE utilization is that designers in general lacked the relevant education/knowledge. Another obstacle is that environmental issues are still not often integrated into the ordinary product development. Instead, these issues are treated as a parallel activity, something that is further influenced by the fact that many DfE methods and tools do not treat environmental issues in relation to other issues. The last but not least important obstacle is related to the expenses associated with DfE.

6.3. Basic requirements a method or tool ought to fulfill in order to become actively used by designers

Whether a method or tool becomes actively used or not by designers does not simply depend on the method or tool itself. As previously discussed, several context-related aspects influence this, for example organizational arrangements, social factors, physical settings and education levels. A method or tool must more or less attract and fulfill requirements raised by different actors in order to be "actively used". This conclusion is based on the discussion in Section 5.1.1. For example, if the designer does not experience satisfaction with the method or tool, there is a risk that the he or she will use the method or tool without really using the outcome (see the discussion about utilization and usefulness of a method or tool in Section 1.4). The outcome that is achieved is, for example, not trusted or regarded as unnecessarily complex to be suitable for the following steps in the product development process. There is also a risk that the designers will skip parts of the method or tool without the manager's knowledge in order to receive a quicker result. This may influence the outcome in a negative way, and furthermore negatively influence the entire product development process. However, at the same time, it is important that the manager's purpose in using the method or tool is communicated to the primary user. This purpose may not be obvious to the designer and therefore not considered.

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[39] A customer is in this context defined as a professional customer.

Depending on the context, different actors' requirements are more or less important. In this research, the focus has been on designers' requirements, since they are considered as key users because of their strong influence on utilization and the quality of the outcome. The conclusion is that it is more or less impossible to discuss requirements for a method or tool unless considering the context in which the method or tool will be utilized. Further, the major actor involved must gain something, for example a more time-efficient product development, from using the method or tool unless it is likely that the utilization will stop or perhaps never even start. As this research has shown, is the major actor in the product development the designer.

Of all designers' related requirements given and validated by the respondents, most are related to designers' aims to fulfill the product performance and keep down the development time. This can be summarized into four major requirements, of which three are interlinked. The conclusion is that a DfE as well as a common method or tool must exhibit the following:

(1) *be easy to adopt and implement* – whether a method or tool fulfills the three following requirements is of lesser importance if it is due to a problem with adoption and implementation and becomes seen as having a low degree of usability, and therefore is not utilized by the designers in their daily work. This requirement is the key for a method or tool to become actively used.

(2) *facilitate designers to fulfill specified requirements* on the presumptive product and at the same time

(3) *reduce the risk that important elements in the product development phase are forgotten.*

Both of these two latter requirements relate to a method or tool's degree of appropriateness. The second and the third requirements are related to the fourth requirement, which is considered by the author to be the most important, that the use of the method or tool:

(4) *must reduce the total calendar time (from start to end) to solve the task.* If the method or tool helps designers to fulfill specified requirements, it will also most likely help them to reduce the calendar time as well as the number of working hours needed to accomplish the product development. This is also something that enables designers to introduce changes in early phases of the product development when changes still are easy to make. Likewise, if the method or tool reduces the risk that important moments in the product development are forgotten, it will most likely have a positive effect and reduce the calendar time and number of working hours needed.

Of course, other requirements can be added and the above four can be divided into more detailed requirements, as described in Chapter 5. But much would be gained if these four requirements were used as a first overall validation of the usefulness of the method or tool. If the result of the validation is positive, further requirements that are more detailed can be used in order to obtain a more detailed validation.

6.4. How method and tool requirements can be utilized to increase the active use in industry of DfE methods and tools

Implementing one of more DfE methods and tools into the product development will not automatically decrease a product's negative environmental impact. What matters more is instead to increase the number of actively utilized methods and tools, i.e. those regularly utilized due to a high degree of appropriateness and usability. In order to do so, the conclusion is that DfE methods and tools must be designed to, in a higher degree, comply to the primary users, in this case designers' requirements for methods and tools.

Furthermore, it is concluded that designers' method and tool requirements can be used to describe the low utilization of DfE methods within industry. This understanding can then, for example, be used to find ways to increase customer requirements, as well as the need for DfE among designers and companies.

Finally, designers' requirements for methods and tools in general and for DfE in particular can be utilized as a means in a selection process to identify the most suitable DfE method or tool, i.e. the one with the comparatively highest usability and appropriateness in the specific context.

6.5. The method and tool paradox

As the studies described in Papers III - VI have shown, the comprehension from the designers' point of view shows an unstructured and haphazard method and tool selection. As also shown, the utilization of DfE-methods and tools among the respondents involved in the studies has been low or non-existent.

Methods and tools are products used to develop new products. It is therefore reasonable to assume that method and tool development ought to follow the same general rules as for other products. At the same time, one of the major reasons for using methods and tools are to, in a systematic and formal way, handle product-related requirements in order to transform them into a product. One underlying reason is to do this in an as efficient way as possible. However, when summarizing the experience from the studies, the conclusion is that there is a lack of formal and well-known aims for and requirements on methods and tools (Papers I - VI). Furthermore, it appears that methods and tools are generally selected in unstructured and ad-hoc ways, and that the general level of formal evaluation of utilized methods and tools seems to be on a low level.

The lack of aims and requirements makes it more or less impossible to accurately measure and prove to what degree the use of a specific method or tool actually facilitates the product development or not. Not even method and tool developers seem to pay this issue any major official attention. It is important to note that this does not imply that the methods and tools used are experienced as poor and worthless and not a value-adding activity for the users or company. Most likely, utilized methods and tools add value to some degree; otherwise, it is likely that the users, in their own subjective and ad-hoc validation of methods and tools based on personal and/or common sense based informal requirements, would abandon them for new methods and tools.

Altogether, this creates a paradox. Methods and tools are aimed to handle requirements and wishes on the presumptive products. At the same time, these are yet developed and selected without any defined requirements.

6.6. Evaluation of research approach and results

This research is based on two research approaches, qualitative research interviews and quantitative questionnaires.

If not managed appropriately, the generalizabilty of the outcomes from qualitative research interviews will be limited. The generalization of the outcome relates for example to the individual respondents and companies. The concepts, validity and reliability are normally used in order to judge the result from qualitative research interviews (Kvale 1983). Validity, which can seen as either internal or external, is according to Kvale (1983) defined as “whether one has in fact investigated what one wished to investigate”.

Internal validity is a question of whether the outcome seems likely for the reader. In order to be able to judge this, the reader must be presented with enough contextual descriptions, where the outcome and conclusions are separated from each other. The participating respondents have validated the internal validity in the research studies (Paper III – V) presented in this thesis. All material, i.e. transcribed interviews and papers/reports, have been sent out, sometimes several times, for review and comments by the respondents before publishing. Seminars have also been used, where the results and conclusion have been discussed and validated. The general impression is that the respondents have agreed with the conclusions and descriptions.

The external validity relates to the generalizability of the results. In order to increase the external validity, different types of companies have been studied. The external validity changes from issue to issue, depending on the number of respondents. Reliability refers to the consistency of the research results. All respondents have given their personal description, and when taken together, provide a nuanced description of the focus area described in this thesis. Regarding the fact that the respondents have given support to the conclusions and descriptions, and that those conclusions can be partly related to other researchers’ studies, increases the reliability of the conclusions in this thesis.

To summarize, the research results presented in this chapter have reached a sufficient level of internal as well as external validity and also a good reliability.

The other research approach, the quantitative survey (Paper VI), was used in order to partly strengthen the reliability and generalizability of some of the outcomes from the interview survey. It was at the same time used to get further answers on the research questions. The number of respondents, in combination with a high response rate and the mix of different types of companies, gives in general a high degree of generalizability.

6.7. Future research

This thesis should be seen as a starting point for ongoing and more comprehensive studies in order to obtain additional empirical and quantitative data concerning the objectives and research questions. Even though this thesis has provided important knowledge, more is needed in order to be able to draw further conclusions and to understand how different contexts influence the method and tool requirements.

One special issue of interest will be to reach an increased understanding of how and to what degree cultural differences, for example between Japan and Europe, influence what requirements designers state on their design methods and tools, and in particular for DfE methods and tools. The assumption is, in general, that cultural differences, especially between countries far away from each other, have a bigger influence on the requirements on methods and tools than cultural differences within the same country. An increased understanding and knowledge about these types of cultural differences is considered to be important in today's more internationalized world, where companies and their employees work world-wide.

Another important issue is to obtain a deeper understanding regarding what requirements designers have for methods and tools that are specifically used in the early phases of the product development. This must be done in order to be able to develop DfE methods and tools that can support the product development in phases where the freedom of action still is relatively high.

Finally, an interesting issue would be to utilize the increased understanding about designers' requirements, not only in their selection of DfE methods and tools, but also in the method and tool developers' development of DfE methods and tools. The aim is to conduct such research in cooperation with selected companies that are about to implement DfE methods and tools, and to do so in cooperation with method and tool developers.

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