DEVELOPING FLEXIBLE PRODUCTS FOR CHANGING ENVIRONMENTS

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Chance favors the prepared mind

Louis Pasteur (1822 - 1895)

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Andreas Bischof
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ABSTRACT

The subject of this thesis is flexibility in product development as an attempt to handle changes in the product environment and uncertainty. The specific focus is on the approach of developing flexible and robust products to handle this challenge.

Changes in the product environment and different kinds of uncertainty are identified to be among the biggest challenges in product development. The crux is, that especially in the early phases of the product development process the knowledge about the finished product is low, and future changes cannot easily be identified. In contrast the possibilities to influence the product are high.

Flexibility is often proposed as an all healing universal tool to handle this challenge. Therefore existing concepts of flexibility in the product development context are analyzed. Yet, current research in this field proves to be an insufficient theoretical basis for understanding, measuring, enhancing and benefitting from the potential of flexibility. Especially the approach of intentionally developing flexible products in order to derive benefits during the development process is far from mature, as well from the academic point of view as from the product developer's point of view.

Therefore a new definition of product flexibility is derived in this work, which specifically takes into account the strong correlation of product flexibility and product robustness. Moreover this research is about answering the following key questions:

- What makes products suitable for changing environments?
- How to develop flexible and robust products for changing environments?
- Is the approach of developing flexible and robust products useful for handling changes in the environment, uncertainty and changes during the development process?

The Design Research Methodology (DRM) approach is carried out in order to answer these questions. In short, one answer to the first question, which is addressed in this work, is that products can be developed specifically flexible and/or robust to handle changing environments.

As the existing approaches for developing either flexible or robust products are considered insufficient a new support for the development process is proposed in this work as the answer to the second question. It consists of 34 design guidelines, which are consolidated from various

approaches. These guidelines are used within the development as guidance, support and reminder of the flexible and robust product design approach.

To answer whether or not the new support and the specific product design are useful to handle changes during the development process a study with engineering designers is carried out: 18 single product developers have to work on the same design task. Ten of them have been instructed with the new guidelines for developing flexible and robust products before the test and are asked to use them on the design task. The other eight product developers have to work on the task without specific instructions. While working on the task requirements and constraints are changed three times in order to simulate the changes, which occur in real product development projects. Data is collected with questionnaires before, during and after the developing, with photo documentation and time measurement; the quality of the results is evaluated by experienced engineering design scientists.

The results of the study are promising, yet controversial as they are not all along with theory. Here it is highlighted that in general the participants working with the new design guidelines are higher motivated and less disturbed by the changes presented during the study. Their results – the generated concepts and designs – are slightly better. However, the differences on quality are not statistically significant. Working with the guidelines seems to cause additional stress for the participants. Nevertheless, the participants evaluated the presented guidelines easy to understand and useful for developing flexible products.

Even though the results are not all satisfactory – not all research questions could be answered clearly – this research underlines the potential of flexibility in product development, especially of developing flexible or robust products. Thus, it provides a solid basis for future research and proposes a useful support for developing flexible products for changing environments.

ZUSAMMENFASSUNG

Die vorliegende Arbeit befasst sich mit Flexibilität in der Produktentwicklung als einen möglichen Ansatz die sich verändernde Produktumgebung und Unsicherheiten in den Griff zu bekommen. Dabei liegt der spezielle Fokus auf der Idee, flexible und robuste Produkte zu entwickeln, um sich den genannten Herausforderungen zu stellen.

Sich ändernde Produktumgebungen und verschiedene Arten der Unsicherheit werden als große Herausforderungen in der Produktentwicklung identifiziert. Die Crux dabei ist, dass besonders in den frühen Phasen des Produktentwicklungsprozesses das Wissen über das spätere Produkt gering ist und zukünftige Änderungen nicht ohne weiteres identifiziert werden können. Im Gegensatz dazu sind die Möglichkeiten das Produkt entsprechend zu beeinflussen hoch. Am Ende der Produktentwicklung kehrt sich das Verhältnis um.

Flexibilität wird oft als universelles Werkzeug vorgeschlagen, um diese Herausforderung in den Griff zu bekommen. Deshalb werden in dieser Arbeit vorhandene Konzepte zur Flexibilität im Kontext der Produktentwicklung analysiert. Es zeigt sich jedoch, dass die gegenwärtige Forschung in diesem Feld nur eine unzureichende theoretische Basis liefert, sowohl zum Verstehen, Messen, Erhöhen, als auch zur Nutzung des Potentials der Flexibilität. Besonders der Ansatz flexible Produkte zu entwickeln, um von den daraus resultierenden Vorteilen schon während des Entwicklungsprozesses zu profitieren, ist sowohl vom akademischen Standpunkt als auch aus Sicht des Produktentwicklers bei weitem nicht ausgereift.

Deshalb wird in dieser Arbeit eine neue Definition für Produktflexibilität hergeleitet, die speziell den engen Zusammenhang von Produktflexibilität und Produktrobustheit berücksichtigt. Außerdem zielt die beschriebene Forschung darauf ab die folgenden Fragen zu beantworten:

- Wie müssen Produkte für sich ändernde Umgebungen beschaffen sein?
- Wie können flexible und robuste Produkte entwickelt werden?
- Ist der Ansatz flexible und robuste Produkte zu entwickeln hilfreich sich ändernde Produktumgebungen, Unsicherheiten und Änderungen während des Entwicklungsprozesses zu bewältigen?

Die vorliegende Arbeit folgt der Design Research Methodology, um die Fragen zu beantworten. Als Antwort auf die erste Frage kann zusammengefasst werden, dass Produkte spezifisch flexibel

und/oder robust entwickelt werden müssen, um Änderungen in der Produktumgebung einfach abzufangen, bzw. umzusetzen.

Da die vorhandenen Ansätze Produkte entweder flexible oder robust zu entwickeln als unzureichend erachtet werden, wird hier – als Antwort auf die zweite Frage – ein neues Werkzeug vorgestellt, welches den Produktentwickler unterstützen soll. Es besteht aus 34 Gestaltungsrichtlinien die aus verschiedenen Ansätzen zusammengetragen und aufbereitet wurden. Diese Richtlinien werden während der Entwicklung als Leitfaden, als Entscheidungshilfe und Gedächtnisstütze bei der Entwicklung von flexiblen und robusten Produkten verwendet.

Um die dritte Frage zu beantworten, ob die Gestaltungsrichtlinien und das spezifische Produktdesign nützlich sind, um Änderungen während der Entwicklung zu bewältigen wird eine Studie mit Produktentwicklern durchgeführt: 18 einzelne Entwickler müssen dieselbe Konstruktionsaufgabe bearbeiten. Zehn von ihnen sind im Vorfeld mit den neuen Richtlinien instruiert worden, um flexible und robuste Produkte zu entwerfen, und werden gebeten, diese bei der Konstruktionsaufgabe nach Möglichkeit anzuwenden. Die anderen neun Produktentwickler müssen die Aufgabe ohne spezifische Instruktionen bearbeiten. Während der Bearbeitung werden Anforderungen und Randbedingungen dreimal geändert.

Während der Studie werden Daten mit Fragebögen vor, während und nach der Bearbeitung, und mittels Fotos und Zeitmessung gesammelt; die Qualität der Ergebnisse wird von erfahrenen Konstruktionswissenschaftlern bewertet.

Die Ergebnisse der Studie sind aussichtsreich, allerdings nicht frei von Widersprüchen und auch nicht immer in Übereinstimmung mit der Theorie. An dieser Stelle sei nur hervorgehoben, dass im Allgemeinen die Teilnehmer, welche mit den neuen Gestaltungsrichtlinien arbeiten, höher motiviert sind und durch die Änderungen in ihrer Arbeit weniger gestört werden. Ihre Resultate sind geringfügig besser als die jener Teilnehmer, welche ohne die Richtlinien die Aufgabe bearbeiten. Die Unterschiede bezüglich der Qualität der Resultate sind jedoch statistisch nicht relevant. Das Arbeiten mit den Richtlinien scheint zu einer zusätzlichen Belastung für die Teilnehmer zu führen.

Dennoch bewerteten die Teilnehmer die neuen Richtlinien als leicht verständlich und nützlich für die Entwicklung flexibler Produkte.

Die Ergebnisse sind nicht ausnahmslos zufriedenstellend; es konnten nicht alle Forschungsfragen endgültig beantwortet werden. Dennoch unterstreicht die beschriebene Forschung das Potential der Flexibilität in der Produktentwicklung, speziell der Entwicklung flexibler und robuster Produkte. So bildet diese Arbeit eine solide Grundlage für die zukünftige Forschung und liefert darüber hinaus ein nützliches Werkzeug, welches die Entwicklung flexibler/robuster Produkte unterstützt.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Motivation

Product development processes are supported by various prescriptive models (e.g. Pahl & Beitz et al. 2007). However, these models are often misunderstood as linear, step-by-step approaches towards the underlying goal – only interrupted by certain milestones or stage gates (Cooper 1994). Reality has proven different (Fricke et al. 2000). Product development is a greatly iterative and complex process with a high likelihood of failure. For example Gericke & Blessing (2006) found that, amongst others, changing aims and goals of a project, imprecise requirements[1], unplanned additional tasks and unexpected difficulties were the main causes of project failure in the context of product development.

Smith (2007, based on Thomke & Reinertsen 1998) presents an industry survey with the undeniable presence of project change in industrial practice (see Table 1-1). All of the more than 200 product developers involved in the survey stated that the requirements do not remain stable throughout a project. Only five percent of the developers had the complete product specifications from the very beginning.

Table 1-1 Industry survey on project change (Smith 2007)

Out of hundreds of projects, how often did the requirements remain stable throughout design?	Never
How many developers had complete specifications before starting design work?	5 percent
On average, what proportion of requirements were specified before design commenced?	54 percent
For each developer who waits for at least 80 percent of the requirements, how many have already started designing?	Five

[1] Requirement definition according to IEEE Standard 1233 (IEEE 1233):
“ A requirement is:
(a) A condition or capability needed by the user to solve a problem or achieve an objective
(b) A condition or capability that must be met or possessed by a system or system component to satisfy a contract, standard, specification, or other formally imposed document
(c) A documented representation of a condition or capability as in definition of (a) or (b)”

Requirement changes in traditional product development projects are undesirable, but are cautiously tolerated when they are inevitable (Jordan et al. 2005). It becomes more and more probable that the initial environment, from which the original product requirements were derived, changes during the products' lifetime (Saleh et al. 2002). Thus, according to IEEE Standard 1233 (IEEE 1233) "requirements that are likely to evolve should be identified" and paid special attention. Fricke et al. (1997) identified five strategies that allow coping with changes:

- Prevention
- Front-loading
- Effectiveness
- Efficiency
- Learning

Prevention aims at complete avoidance of changes: The product development has to be well planned, take into account all possible future scenarios, and has to be carried out assiduously. The idea behind the strategy is "doing it right first time". Front-loading aims at putting a lot of product development effort (and resources) at the front end of the development process where handling changes is easier, less expensive and with more options to influence the product. Effectiveness aims at avoiding and reducing the negative effects of changes; this way the occurrence of changes is accepted, but not their negative impact on the development process. The idea behind efficiency is to make the inevitable change (procedure) as efficient – fast and cheap – as possible. Learning is a basic approach, which supports the other four. By learning from the past, changes in the present can be avoided, detected earlier, and handled more effectively and more efficiently.

Saleh et al. (2003) propose a product oriented approach to coping with changes that integrates all five strategies suggested above: Instead of attempting to freeze the requirements as early as possible it is preferable that product developers "design for change", or embed flexibility into the product design.

From Reactive to Proactive Flexibility

Flexibility has proven to be a good tool for coping with uncertain and changing environments (Thomke & Robertson 1998). However, flexibility in product development is often an afterthought. Engineering design projects are analyzed retrospectively and flexibility in one form or another (see Chapter 2 and Chapter 3) is detected as a cornerstone of project success (Thomke 1997a). While firefighting is commonly used in development projects (Black & Repenning 2001), actively implemented flexibility is hardly to be found in engineering design research and practice. It is proposed here to proactively implement flexibility into product development – specifically into the product - and thus benefit from the advantages of flexibility. This approach is similar to the one analyzed and proposed by Harlou (2006): “from reactive to proactive re-use” has already led to benefits in industrial projects. Proactively implementing flexibility in a development project for initial validation has also led to subjectively rated positive results (Bischof et al. 2006).

However, the approach of developing flexible products to handle changes caused by uncertain and changing environments is still a vague concept; hardly any tools and methods exist to support the product developers. Therefore, this work is to substantiate the approach of developing flexible and robust products (see definitions Section 2.4.2) and evaluate its benefits.

1.2 Aims

Comparing the number of hits in the academic database Web of Science on “flexibility”, “optimality” and “robustness” and the number of hits on the popular search engine Google, Saleh et al. (2008) draw the conclusion that “flexibility, despite its popularity, is not yet an academically mature concept” (Figure 2-4). Nevertheless flexibility is recognized as a critical attribute of a system, a process, or an organization to cope with uncertainty and change (Saleh et al. 2008). One aim of this work is to understand product (development) flexibility in the context of changing and uncertain environments in order to close the gap between popularity and academic understanding of flexibility.

In contrast to other scientific disciplines – e.g. natural sciences – engineering design research is not only about understanding phenomena. Besides gaining academic understanding it is expected to provide practical benefits for design engineers and product developers (Cross et al. 1981, Broadbent 1981). Academia and industry have recognized the growing importance of structured, scientific, and industrially tested theories, methods and tools for design. However, theoretical research towards establishing the science of design has not produced enough practical results (Dorst 2008). A second aim of this work is to provide a support[2] for product developers for developing flexible and robust products for changing environments.

[2] Here the term *support* is understood as by Blessing & Chakrabarti (2009): “The term *support* is used to cover the possible means, aids and measures that can be used to improve design. This includes strategies, methodologies, procedures, methods, techniques, software tools, guidelines, information sources, etc., addressing one or more aspects of design. Support thus covers a spectrum as diverse as: checklists for identifying requirements, software for calculating stresses, drawing aids, guidelines for embodiment design, tools for product life-cycle assessment, project management tools, procedures for introducing methods, plans for new organisational structures, standards and regulations.”

1.2.1 **Practical Aims for Product Developers**

Changing environments including changing customer requirements generate more demands for product development. Products should be developed in "short iterations answering to the rapid external changes and keeping up a high quality level" (Rikkarainan & Passoja 2005). This idea derived from a software case study is the basic concept underlying the approach illustrated in Figure 1-1.

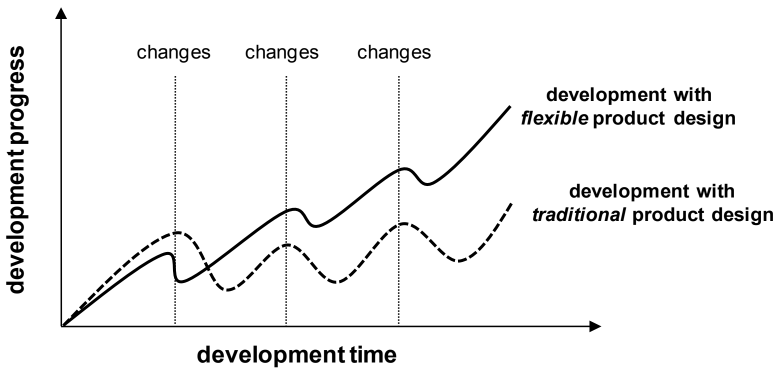


Figure 1-1 Development progress for products with flexible and products with classical product design over time (Bischof & Blessing 2007, based on Cebon et al. 2002)

By developing products with a flexible design, changes during the development process and after product launch can be handled easier. Thus, development progress is faster. The aims of this work for product development practitioners are the following:

- To give one possible solution to the stated problem of developing products in uncertain and changing environments
- To provide a support for the development of flexible and robust products to ease handling of uncertain and changing requirements.
-

1.2.2 **Scientific Aims & Key Questions**

Science is about gaining knowledge and enhancing understanding. In particular, the scientific aim of this work is about understanding the phenomenon of flexibility in product development. It is about finding out if product flexibility is a useful way to cope with changing environments.

A new model of product flexibility is set up based on existing theories and the support provided for product developing practitioners (see Section 1.2.1) is evaluated. Thus, this work contributes to existing knowledge of flexibility in product development in general and to the understanding of flexible products in particular. Therefore the main scientific aims of this work are to verify the hypotheses (see Section 5.1) and to answer the research questions (see Section 5.1):

K1: What makes products suitable for changing environments?

K2: How to develop flexible and robust products for changing environments?

K3: Is the approach of developing flexible and robust products useful for handling changes in the environment, uncertainty, and changes during the development process?

1.3 Scope

One aim of this work is to provide product developers a useful support for the development of flexible products. Thus, the scope of this work is on the product and on the development process from a practitioning product developer's point of view. The customers' view on product flexibility, especially after product launch, is of less importance for this work. The difference is explained in Table 1-2. The customers are usually only interested in the finished products. For example they benefit from the flexibility provided by a sofa bed – being either a sofa or a bed at limited required space. The flexibility of a desktop computer is beneficial for both customer and product developer, as the customer benefits from the possibility of easily changing and upgrading the computer, while the company benefits by the use of identical parts[3] in different products and produce them in of higher production volume. Some flexible products are only beneficial for the company, respectively the developing engineers: The platform strategy, often applied in automotive industry, can help reducing costs, developing time and effort for the company, while the customer might not even notice the flexibility of the product. The scope of this work is on the latter category of product flexibility: these that are beneficial for the company, at least short-term (only in long-term, the customer will benefit as processes are shorter, thus cheaper).

[3] In Cambridge Dictionary (2007) part is defined as "one of the pieces that together form a machine or some type of equipment."

Table 1-2 Different stakeholder perspectives on product flexibility

stakeholder	flexible product example
customer	sleeping sofa
customer & company	desktop computer
company/product developer	car platform

Products can provide an unintended flexibility (Dix 2007) and affordances (Maier & Fadel 2001). E.g. books can be used as doorstopper. This flexibility in use is not designed in the product on purpose. Thus, this flexibility in use is not researched in this work.

Various definitions of products exist (e.g. Pahl & Beitz et al. 2007, Ulrich & Eppinger 1995, Otto & Wood 2001). They can include intangible products such as software and services (Thomke 2006). Even though the development processes, the applied methods and methodologies and the products' properties[4] can be similar, the scope here is narrowed to material, tangible, technical products.

Research in the product development discipline has in general two main domains: On the one hand the products, their properties, their behavior in the context of market and customers, their use-phase. On the other hand there are the processes necessary to create a (material) product. These mainly include all other phases from the product life-cycle, such as development and manufacturing.

Flexibility can be applied to both domains – product and process. The benefit or impact from applying flexibility can either be in the same domain (product-product and process-process, see sectors I and III in Figure 1-2) or cross domain (see sectors II and IV). Applying flexibility to the product, developing flexible products, can be beneficial for the development process (II), while process flexibility can have positive impact on the product being developed (IV).

[4] The *properties* (…) describe the product's behavior (e.g. weight, safety and reliability, aesthetic properties, but also things like "manufacturability", "assemblability", "testability", "environmental friendliness", cost). They cannot be directly influenced by the developer/designer."
The product properties are not to be mixed up with product *characteristics*, which are defined by Weber (2007) as follows:
"Characteristics (…) describe the structure, shape, dimensions, materials and surfaces of a product …). They can be directly influenced or determined by the development engineer/designer.

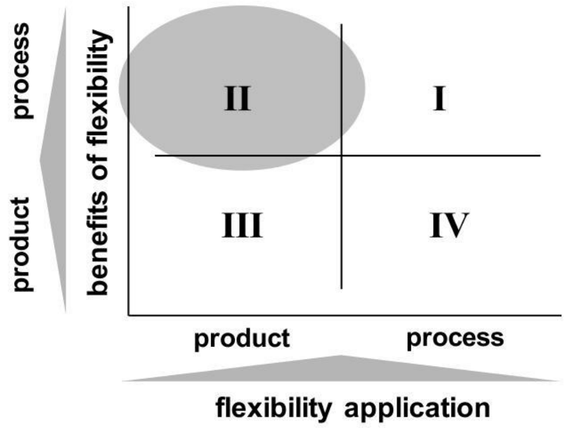


Figure 1-2 Domain of flexibility application and domain benefitting from flexibility

The scope of this work is on the product-process domain (sector II in Figure 1-2). This means that products are intentionally developed flexible (flexible product) in order to derive benefits of the flexibility already during the product development process. Benefits for the customer due to the flexible product and long term benefits for the company are not analyzed.

1.4 Approach

"The engineering scientist analyses what is, imagines what should be, creates what has never been and analyses the result of the creation" (Sohlenius 1990).

This statement on scientific work within the field of engineering summarizes the Design Research Methodology (DRM) proposed by Blessing & Chakrabarti (1994, 2009). The DRM is a four-stage methodology which serves as the basic approach for this work. The methodology aims to provide a deep understanding of phenomena in engineering design, as well as to derive support, i.e. methods, tools and guidelines, to improve the design process and its outcomes. Figure 1-3 illustrates the DRM with its four stages.

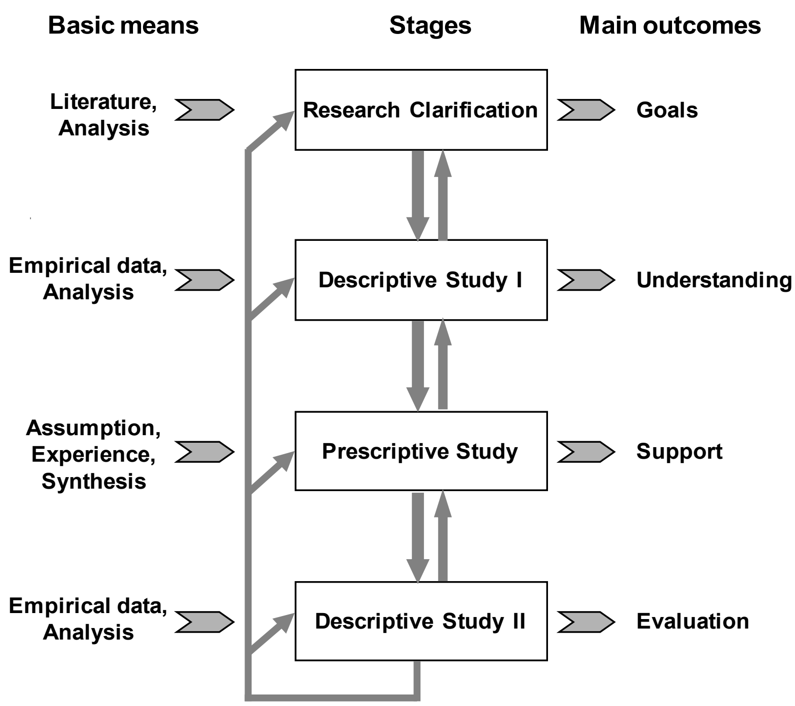


Figure 1-3 The DRM framework (Blessing & Chakrabarti 2009)

The first stage *Research Clarification* is carried out in order to define the goals, context and scope of the work and to get an initial understanding of the research problem or rather the research area. If possible, measurable criteria are derived that are used for the evaluation in the last stage.

In the second stage, empirical data from literature or e.g. generated by observation, is analyzed. The main outcome of this *Descriptive Study I* is a deeper understanding of the researched phenomenon. Extensive literature studies, experiments and observations are used to gain a coherent knowledge. This knowledge includes the influencing factors on the research topic.

Independent of the fact whether the research is theory based (deduction) or problem based (induction) (Blackenfelt 2001) it usually aims at the improvement of the current situation (Blessing & Chakrabarti 2009). Therefore a support is derived from assumptions, experiences, syntheses and the results of *Descriptive Study I*. This method, tool, guideline etc. is the main outcome of the third stage, the *Prescriptive Study*.

The last stage *Descriptive Study II* aims at validating the developed support. Feedback loops and iterations to the earlier stages are used to improve the understanding and support or to redefine the goals, aims and scope of the research.

1.5 Outline of the Dissertation

In the first chapter of this work the motivation has been described: namely a challenging product development context with uncertain and changing environment. Aims and scope have been described in Sections 1.2 and 1.3. It is difficult to determine measurable criteria for evaluating the success of developed support at this early stage and therefore this is not discussed until Descriptive Study II, where the research questions and hypotheses are formulated. In order to back up the literature study for the Research Clarification and the Descriptive Study I this work is embedded in a participant observation project (Bischof et al. 2006, Goralczyk & Bischof 2006, Goralczyk et al. 2009, see bioreactor example in Section 2.4.4). The Descriptive Study I and its outcomes are presented in Chapters 2 and 3. While Chapter 2 explains the phenomenon of flexibility in product development, Chapter 3 focuses on understanding the state of the art of developing flexible and robust products. A support for the development process is proposed in the fourth chapter. It consists of 34 design guidelines to support the development of flexible and robust products. The evaluation (Descriptive Study II) of the developed support is described in Chapters 5 and 6. Chapter 5 concerns the method of evaluation, while Chapter 6 presents the results of the evaluation. In chapter 7 the whole research is summarized and suggestions for future research are given

2 FLEXIBILITY IN UNCERTAIN AND CHANGING ENVIRONMENTS

This chapter is highlighting the importance of flexibility in context of uncertain and changing environments. Therefore uncertain and changing environments are described as well as the challenges they cause in product development (see Section 2.1). A general definition of flexibility as understood in this work is provided and the nature and purpose of flexibility is discussed (see Section 2.2). More specific aspects of flexibility in the context of product development are presented and explained in detail (see Section 2.3). This way Section 2.3 aims at providing a better understanding of the basic idea behind the approach proposed to cope with uncertain and changing environments. Moreover the concept of flexibility, with its manifold definitions, characteristics and inherent fuzziness, is specified for the product development context. In Section 2.4 flexible products are defined. The correlation of flexibility and robustness is explained, as well as the purpose of product flexibility. Examples of flexible products are given, trade-offs of product flexibility is described and the measurement of product flexibility is briefly discussed.

2.1 Uncertain and Changing Environments

Uncertain and changing environments are among the biggest challenges in product development. Therefore this section highlights the most important aspects of uncertain and changing environments to create a basic understanding of these phenomena and how flexibility can fit in as one solution to handle this challenge in product development.

2.1.1 Uncertain Environments

Uncertainty characterizes the product development process, especially the early phases (Chen & Yuan 1999). Handling this uncertainty is one of the main challenges for the developer. Uncertainty in the product development context can be classified and explained in different ways: Browning (1998) classifies uncertainty, which he uses synonymously with risk when it appears in the development process, by the areas that are influenced by it. The six main categories of risk are schedule, performance, technology, costs, market and business. DeMeyer et al. (2002) classify different types of uncertainty by the management techniques, which should be applied to handle uncertainty. Milliken (1987) describes uncertainty in product development as a subjectively perceived information deficit. Even though explanations and definitions are countless and diverse, they all have a common core. Uncertainty is high in the beginning of the development process and thus the risk of making wrong decisions is high, while information about product performance, technology and market increases during the later phases and consequently uncertainty and risk are reduced (see Figure 2-1). It is therefore difficult to determine the product specifications in the early phases.

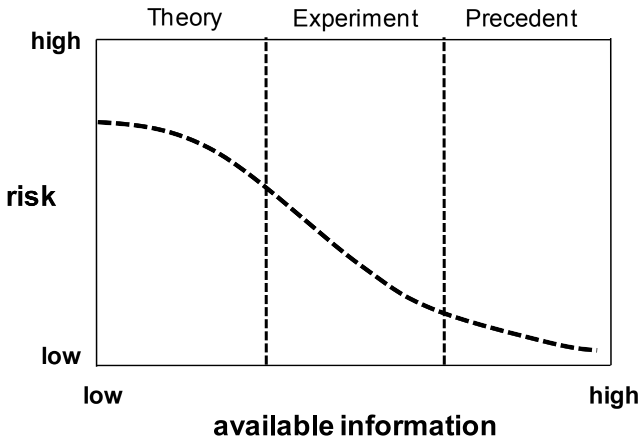


Figure 2-1 Risk decrease with availability of useful information (Browning et al. 2002)

The uncertainties in industrial practice differ depending on type of industry. For example, the main uncertainties for commercial aircraft industries are travel demand, demographic shifts, regulations and competition (Haberfellner & de Weck 2005). In automotive industry customer decisions and styling decisions are highlighted, while for all vehicle systems the major uncertainties are fuel prices, shifting customer preferences, competition and regulations (Carney 2004). It is due to these uncertainties that, according to Connel & Shafer (1989), only 50% of the requirements in software development projects are set correctly at the beginning. Andersson (2003) states that it is and probably always will be impossible to achieve a complete description of all requirements specifications of a product, but that is "nevertheless worth aiming for, since a missed requirement can cause major iterations in a development project."

Uncertainty in development projects can be reduced in several ways. Smith (2007) suggests three approaches: first, eliminating uncertainty caused by the customers by intensifying the information exchange between company and customers; the second approach is experimentation, which "is more of a general tool that allows you to understand customers, markets, technologies, design choices and manufacturing difficulties better, thus reducing uncertainty" (Smith 2007). A third approach to handle uncertainty in product development is to increase flexibility. This third approach is analyzed and tested in this work.

2.1.2 Changing Environments

Not only are the environment and requirements unknown and uncertain during development, but they are changing as well: Almefelt et al. (2003, Almefelt 2005) analyzed the requirements progress in the automotive industry. They found that especially requirements related to structural components and the packaging related requirements constantly evolved and became stricter in the six analyzed projects. Other requirements (structural behavior and material concept) decline due to new knowledge gained by tests and analyses or are "strongly promoted in the beginning", but then "watered-down and become less and less prioritized" (Almefelt et al. 2003).

"Little appears stable" (Iansiti 1995). "Individual requirements are not static throughout the project, but rather changed, in one or more steps" (Almefelt et al. 2003). The environments are rapidly changing and are characterized by "virtually unprecedented levels of technical and market uncertainty" (Iansiti 1995). Customer base, high number of competitors, and the technological possibilities are designated by "frequent and substantial change" (Iansiti 1995). The causes of these changes are numerous and diverse:

- New customer needs and requirements (Schulz & Fricke 1999, Martin 1999, Eckert et al. 2003, Fricke 2006)
- Feedback and customer complaint (Fricke 2006)
- Cost reduction (Martin 1999, Martin & Ishii 2002)
- Time (Eckert et al. 2003)
- Technological evolution (Schulz & Fricke 1999)
- Competitor (Schulz & Fricke 1999)
- Complexity of system environment (Schulz & Fricke 1999)
- Changes in environment: physical, political, technological and economic environments or conditions (Jordan et al. 2005)
- Increasing system complexity (Ring & Fricke 1998)
- Change propagation (Clarkson et al. 2001)
- Market research (Sanderson & Utzumeri 1995)
- (New) regulations and standards (Martin 1999, Martin & Ishii 2002)
- Discipline on decisions (Fricke & Gebhard 1996)
- Realizability (Wildemann 1994)
- Degree of innovation (Gemmerich 1995)
- Ill communication (Fricke 2006).

Unstable and temporary customer needs are often highlighted as the main problem (Thomke 1997b, Blessing & Schmidt-Kretschmer 2004). Customers often have problems specifying their needs and wishes (Thomke & Reinertsen 1998). These changes have serious effects on product development projects: The changes are “surprisingly complex” (Earl et al. 2005). They enhance the costs (Wertz & Larson 1996, Fricke 2006) and are “important for project success” (Fricke 2006). The Standish Group (1995) found that “changing requirements and specifications are the main problem of unsuccessful projects”. The Standish Group (1995) concludes that for “every 100 projects that start, there are 94 restarts. This does not mean that 94 of 100 will have one restart, some projects can have several restarts.“ (The data is based on surveys and personal interviews with a sample size of 365 respondents and a represented 8380 applications). Even though this number seems to be at the upper end of the scale, the general trend of costly and time-consuming redesign and iterations caused by changes during the development is well supported (Boehm et al. 1984, Feld 1990, Eger et al. 2003, Wynn et al. 2007, Paetzold 2008). Whiting (1991) found that 47% of the work in product development processes has to be repeated. 30% of the work is caused by changes (Wildemann 1993, Fricke & Gebhard 1996, Fricke 2006). Nevertheless, this redesign cannot compensate the negative effect of changes. Changes “lead to lower quality” (Fricke 2006); 30-35% of all products fail to meet customers’ expectations (Sieger et al. 2000).

Figure 2-2 below shows the *Rule of ten*. The figure illustrates that the cost of changes (or the costs of failure detection) rises by a factor of ten each phase in product development (e.g. VDI 2247 (1994)). There are different definitions of the phases, for example according to VDI standard 2247 (VDI 1994) the phases are defined as development, manufacturing, and use. Blanchard (1997) defines the following phases: conceptual design, preliminary design, detailed design, and production. Varying definitions make this rule unclear. There are serious doubts about the correctness of the factor ten (Boehm & Turner 2003, Smith 2007), but various researchers in product development support basic/qualitative validity for this rule of thumb (Boehm 1981, Fricke 2006, VDI 1994, Riepe 2003, Herbertsson 1995, Smith & Reinertsen 1998, Wheelwright & Clark 1992, Blanchard 1997).

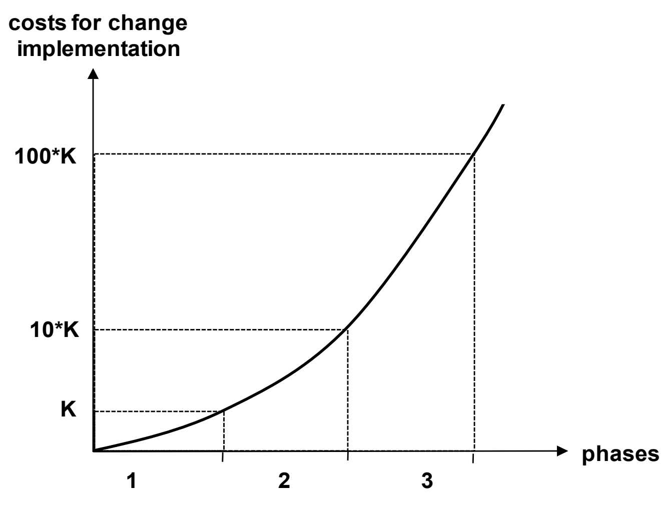


Figure 2-2 Rule of ten

The later changes appear in the product development process, the more costly they are. “Doing it right the first time” is an illusion (Fricke 2006). Specifying the product with all characteristics and requirements at the beginning of the process does not seem to fit with reality (Fricke 2006). “So it is not that specifications seldom remain constant during development; it is that they never do. The concept of frozen requirements is complete fiction in the real world” (Smith 2007, Table 1-1). Freezing requirements, even after the launch of complex products, is unrealistic (Jordan et al. 2005).

Figure 2-3 illustrates the correlation of determined product characteristics, needed development time, and effort (costs) over product development process phases. Qualitatively similar trends were directly derived from industrial data (BMW 1992). The figure shows that in general it is easier to influence products in the early phases, when the product characteristics are not completely specified (BMW 1992, Riepe 2003). After the requirement phase very little of the product is determined. The possibility to influence a project decreases over its execution and therefore the earlier the intervention the more options there are for influencing it.

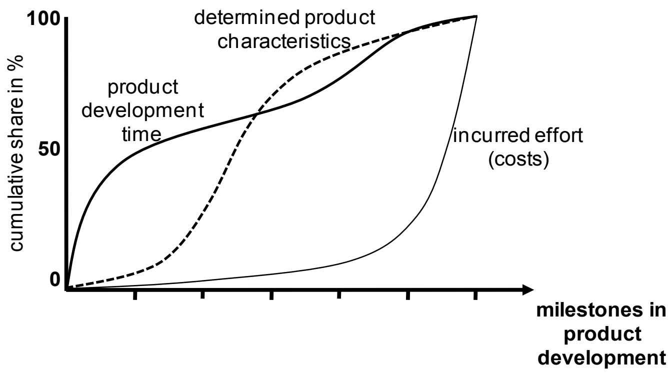


Figure 2-3 Progression of determined product characteristics, development time needed, and effort over product development process (Riepe 2003)

The following section about flexibility shall help to understand how the possibility of influencing the product even in the later phases can be increased. Therefore flexibility is explained in general, its relevance in product development and the implementation of flexibility in flexible products.

2.2 Importance of Flexibility

The approach of applying flexibility in product development, either products or processes, is not all new. However, in order to distinguish between an approach taken with the focus on flexibility, and other approaches where flexibility is not the main target, the latter ones are called classical and/or traditional approaches throughout this work. The same distinction is valid for flexible products and classical/traditional products. These definitions have only been chosen to clarify the difference and are by no means a way in which to devaluate either of the approaches.

Flexibility is recognized as important in academia as well as in industry (e.g. Carlson 1989, Ku 1995, Calvo et al. 2006). In product development and related disciplines, flexibility is mentioned mostly in the context of uncertainty, changes and limited predictability (e.g. Evans 1991, Fricke et al. 2000, Saleh et al. 2008).

The importance and presence of flexibility outside academia is illustrated by Saleh et al. (2008), comparing the number of hits on the terms optimal, robust and flexible in both a popular search engine and a scientific database (Figure 2-4).

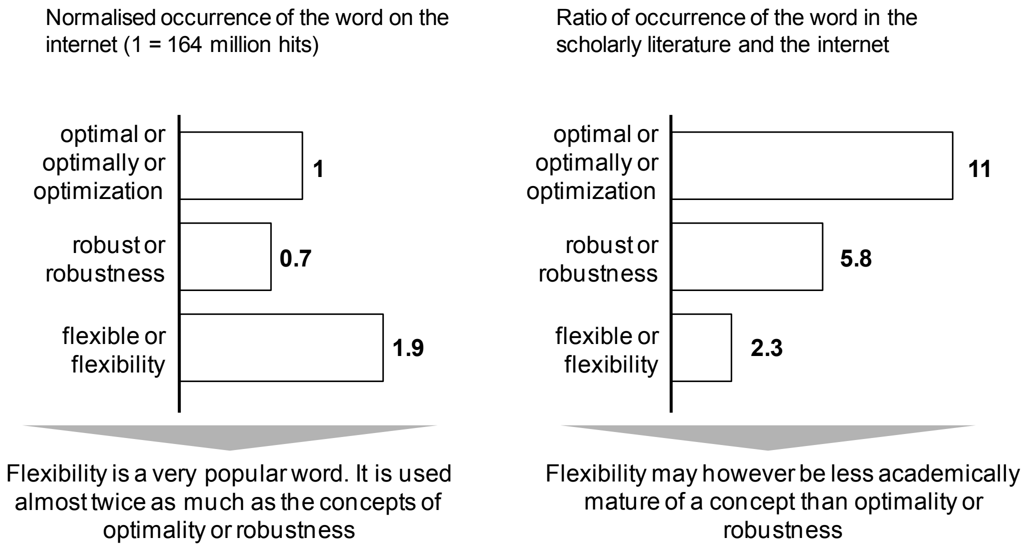


Figure 2-4 Relative popularity (left) and academically maturity (right) of flexibility compared with the concepts of robustness and optimality (as of 1 October 2005, Saleh et al. 2008)

The figure above shows that in general language usage "flexibility is used twice as much as the concepts of robustness or optimality; however, it is used significantly less in an academic context than robustness and optimality – 2.5 and five times less often, respectively. (…) the numbers do suggest that flexibility, despite its popularity, is not academically as mature of a concept as robustness or optimality" (Saleh et al. 2008).

Even though flexibility is recognized as important for product development, its meaning is still vague: Ku (1995) noted that "the importance of flexibility in planning is widely acknowledged, but the concept is rarely defined, much less quantified." In the following, various definitions are presented and discussed in order to reduce the fuzziness of the term flexibility.

2.2.1 Flexibility Definitions

In the article "The Magic Word Flexibility" Kickert (1985) criticizes the over-use of the word flexibility as the ultimate solution to various problems in industry and other domains. He convincingly shows that "it is rather gratuitous to propose the magic word flexibility as a solution to various problems, as the concept appears to be [still] unclear, to put it mildly' (Kickert 1985, p. 28)" (Saleh et al. 2008). Saleh et al. (2008) conclude that as a first step it might help "to be more precise in use of the word, especially in the context of engineering design."

For the manufacturing context Sethi & Sethi (1990) identified over 50 definitions of different types of flexibility. However, they emphasize that these definitions are often imprecise and naïve (Sethi & Sethi 1990). Upton (1995) suggested that the concept of flexibility is where the concept of quality was some 20 years ago, "vague and difficult to improve, yet critical to competitiveness."

According to the Cambridge Dictionary (2007) flexible means "able to change or be changed easily according to the situation". Several literature studies try to derive the basis of all the different definitions that are in use and form a new general, understandable, yet precise new one. Gupta & Goyal (1989) found that intrinsic to the notion of flexibility is the ability or potential to change and adapt to a range of states; because it is more about a potential to change it is difficult to analyze, describe or to measure.

However, Thomke (1997a) defines flexibility (in general, but derived from analyzing process flexibility) in a way that allows indirect and relative measure:

"Development flexibility can be expressed as a function of the incremental economic cost of modifying a product as a response to changes that are external (e.g. a change in customer needs) or internal (e.g. discovering a better technical solution) to the development process. The higher the economic cost of modifying a product, the lower the development flexibility" (Thomke 1998).

By introducing costs, Thomke's definition allows an indirect measure of process and/or product flexibility. However, it is missing two important aspects brought up by Saleh et al. (2008): The absence of irreversibility and of rigid commitments. This means that flexibility is not understood a one-time option, but decisions made can be reversibly[5] canceled throughout the whole development process and be replaced by new decisions; no rigid commitments are made.

Based on Thomke's definition of flexibility and including Saleh's aspect of reversibility, a new definition is proposed in order to make the concept behind flexibility more understandable and applicable:

---

[5] *Reversible* is defined as (Cambridge Dictionary 2007): "If something is reversible, it can be changed back to what it was before."

Flexibility is the ability to adapt to changes easily and reversibly – while easily is understood as economically and rapidly and reversibly as changeably back to what it was before.

2.2.2 **Purpose**

Flexibility goes hand in hand with uncertainty and changes. However, coping with either of those is not the only purpose of flexibility. Various and more specific purposes behind applying flexibility can be found in literature that are:

- Handling complexity (Thomke & Reinertsen 1998)
- Reducing technical risks and gaps (General Accounting Office 2001, Saleh et al. 2008)
- Accelerating processes (Iansiti 1995)
- Increasing efficiency (Iansiti 1995)
- Enhancing variety (Blackenfelt 2001)
- Delaying decisions (Ward et al. 1995).

Figure 2-5 illustrates an example given by Iansiti (1995) on the average engineering resources used in flexible and traditional development projects.

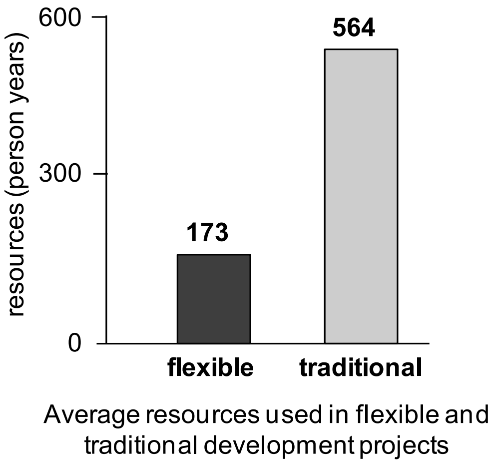


Figure 2-5 Average engineering resources used by project in traditional and flexible project clusters (Iansiti 1995)

The data presented by Iansiti (1995) is corrected for different contents of the analyzed projects. It should "be interpreted as the person years of engineering effort required by each project to conceptualize and develop an average processor module." Based on these findings he draws the conclusion that "Flexible projects are much more productive – using, on average, less than a third of the resources required by traditional projects" (Iansiti 1995).

One core purpose of flexibility is to make better decisions. Merton (1997), Nobel laureate in economics, stated: "The future is uncertain, and in an uncertain environment, having the flexibility to decide what to do after some of that uncertainty is resolved definitely has value." Thus, by applying flexibility to a project decisions can be delayed. More information can therefore be gathered before a decision is taken, which is likely to result in a better decision.

2.3 Flexibility in Product Development

If flexibility leads to more adequate decisions there is no doubt about its usefulness in product development. In order to realize the benefits of flexibility in product development different approaches have been implemented, tested, analyzed and described in the business and the scientific literature (e.g. Schulz & Fricke 1999). Figure 2-6 below illustrates a simplified version of the product life cycle (based on Feldhusen & Gebhardt 2008), and different forms of flexibility that play a role in each of the phases. Each of the forms of flexibility is discussed in the following subsections.

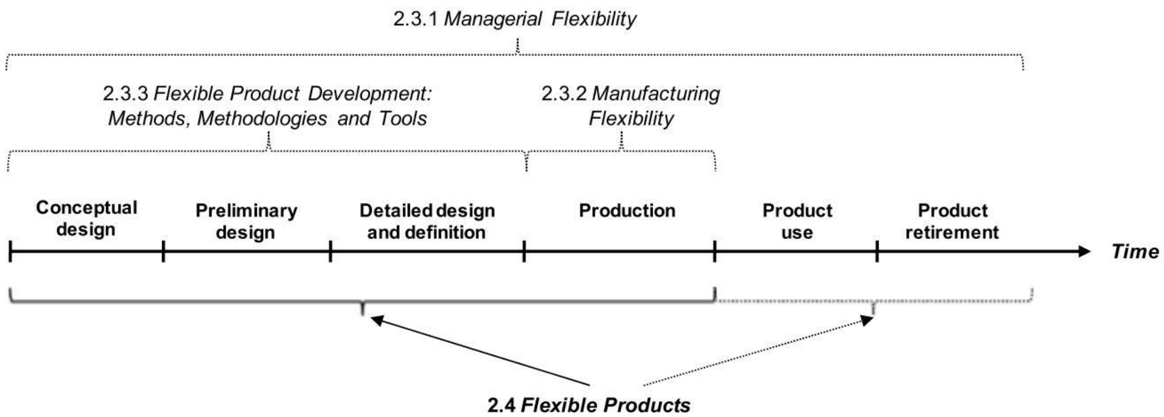


Figure 2-6 Product life cycle phases associated with different forms of flexibility

Strategic flexibility (see Section 2.3.1) is not directly related to a particular phase of the product development phase or product life cycle phase. Flexible Manufacturing as described in Section 2.3.2 concentrates on the production phase of the life cycle. It is not the focus of this work; neither are product flexibility in the product use phase and in the product retirement phases. Flexible product development methods, methodologies and tools used to enhance the process flexibility are described in Section 2.3.3. In Section 2.4 product flexibility is explained. Usually this would be related to the use phase and to the retirement phase. As illustrated in Figure 1-2 in this work the application of product flexibility is used to already derive benefits in the development phase. Thus, it is assigned to the whole product life, while the focus of this work is the development phases.

2.3.1 Managerial Flexibility

Flexibility has strongly caught the interest of management disciplines (Saleh et al. 2008). In hypercompetitive (Fricke et al. 2000), fast changing and highly uncertain markets flexibility is of high value (Copeland & Keenan 1998), as management decisions can be proven invalid or incorrect within a short time (Evans 1991).

Managerial flexibility "is defined as the ability of management to adjust the course of a project by acting in response to the resolution of (…) uncertainty over time" (Saleh et al. 2008 citing Trigeorgis & Mason 1987, Amram & Kulatilaka 1999). In other words, managerial or strategic "flexibility reduces a project's exposure to market uncertainty" (Saleh et al. 2003). This can for instance be achieved by delaying the decision of an investment.

According to Smith (2007) a direct correlation exists between flexibility and the level of innovation of a project. The more innovative the product being developed is, the higher the benefits of flexibility are. More factors influencing the need for flexibility are listed below (Smith 2007):

- Speed of market changes
- Effectiveness of changes on product line
- Probability of changes affecting product line
- Maturity of applied technology
- Stability of customer needs
- Market flux
- Discipline or branch in which company is situated.

The degree of flexibility for strategic decisions has to be chosen based on these factors. Various tools and methods are proposed in scientific and business literature:

- Prepare and involve stakeholders for change (Daniels & Mathers 1997)
- Achieve flexibility by empowering people (Peters 1987)
- Preoccupy with failure – fail early and often, but do not make mistakes (Weick & Sutcliffe 2007, Thomke 2003)
- Eliminate bureaucratic rules and humiliation conditions (Peters 1987)
- Simplify (Peters 1987)
- Create a spirit of (rapid) experimenting (Thomke 2003)
- Apply specific working styles like cloud computing, extreme programming, pair programming (Boehm & Turner 2003).

Managerial flexibility can be concluded as: "Embrace change rather than fight it" (Boehm & Turner 2003). It is more about creating a mindset of flexibility than about the methods or tools applied to achieve this goal. The people are most important for change (Smith 2007). Thus, all the people involved in the development project (and use of the product) have to be informed and prepared for changes in order to create a positive spirit for changes.

2.3.2 Manufacturing Flexibility

Manufacturing is one phase of a product's life cycle. Flexibility has been embraced for a couple of decades (Smith 2007). There are three general aims behind it: One aim of manufacturing flexibility is to compensate fluctuation in demand. The second aim is to create a greater product variety, as the manufacturing flexibility eases the production of different products. A third aim of enhancing manufacturing flexibility is to keep the production process running without interruptions and reducing any disruption to a minimum. For example, Toyota has implemented a technique called *single minute exchange of die* (SMED) (Shingo 1989). It allows the possibility to change tools, e.g. dies to stamp body panels, "in minutes rather than days, thus changing from making one part to making another one far more easily" (Smith 2007). This way, interruptions in the manufacturing process are reduced.

Figure 2-7 illustrates the correlation of product flexibility and manufacturing flexibility. According to Blackenfelt (2001, Ulrich 1995a) manufacturing flexibility is mainly applied in order to create a greater (product) variety. Manufacturing flexibility can be combined with product flexibility (see Section 2.4)

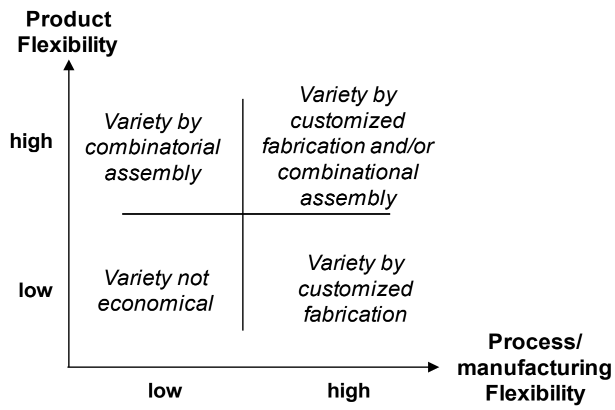


Figure 2-7 Product or process flexibility adapted from Ulrich (1995a), by Blackenfelt (2001)

Haberfellner & de Weck (2005) provide two examples of manufacturing flexibility. The first is from the food processing industry (Nestlé), where the major product innovations are marketing driven. The manufacturers have to be very careful in choosing "new technologies [for food processing, packaging and distribution] and factory configurations and will have a strong need for agility during the phase of (...) planning, evaluation and decision [taking] and even for the design and manufacturing phase of this equipment" (Haberfellner & de Weck 2005). This way flexible manufacturing helps the company to determine later, which food product is produced and how it is produced. Thus there is more time to figure out the customers' preferences.

The second example for manufacturing flexibility is from the toy industry (Mattel). Due to high competitiveness, the toy industry endeavors a seasonal portfolio change. Extensive marketing surveys are carried out to define which products will be "blockbuster-products". Therefore manufacturing decisions are "delayed as far as possible to understand what competitors will be offering and what the latest emerging fashion might be" (Haberfellner & de Weck 2005).

Flexibility in manufacturing is often achieved by using flexible manufacturing systems (FMS), which can be configured in various ways and for a high number of different manufacturing purposes. Dove (1999) analyzed these FMS and derived ten fundamental principles for flexible systems and products that can be clustered in three categories:

- Reusability:
  - self contained units
  - plug compatibility
  - facilitated reuse
- Reconfigurability:
  - nonhierarchical interaction
  - deferred commitment
  - distributed control & information
  - self organizing relationships
- Scalability:
  - flexible capacity
  - unit redundancy
  - evolving standard

Similar principles can be found for flexible products (see Chapter 3). These principles can be used to derive design guidelines to support the development of flexible products – the basic idea of this work (see Chapter 4).

2.3.3 Flexible Product Development: Methods, Methodologies and Tools

Flexibility in product development helps to make changes to a product with minimal disruption, even relatively late into its development process. The less disruptive the changes are, the more flexible the development process is (Smith 2007).

Flexible product development is strongly associated with (flexible) development strategy. Product developers are well advised to have flexibility as an explicit objective in their processes (Thomke 1997b).

Similar to strategic flexibility, flexible development processes are a state of mind. Hardly any methodical support exists that specifically aims at making the processes flexible. Even though flexible processes in product development have been investigated (e.g. Meißner et al. 2005, Meißner & Blessing 2006, Ponn 2007) they are so far more or less new interpretations of existing methods, methodologies and tools: Reinicke (2004) states, that new situations do not always have to be handled with new methods, but rather with an adaption of existing methods as proposed by Zanker (1999). Fricke (1996) analyzed and compared different approaches of engineering designers. He found that the most successful designers took a flexible-methodical approach: They made use of supporting methodologies (e.g. Pahl & Beitz et al. 2007, VDI 2221 (1993)), but instead of strictly following this methodology the most successful designers interpreted it in a more flexible way and continued the development process without methodical assistance, when they could achieve better progress this way.

Ward & Sobek II (1996) point out, that the power of Toyota's product development paradigm does not result from the application of new (computer-aided) tools, but rather from a new engineering culture, which allows to flexibly adapt each development processes for every new project.

Figure 2-8 illustrates the difference between a traditional product development process (Andreasen 1987) and a more flexible approach. By applying the traditional approach, product developers have to span a solution space, select the optimal solution and carry on the development from this single point. In contrast to that the flexible approach does not necessarily require a definite solution for each phase. Instead of selecting a single solution, a solution range is selected from which the process can be continued.

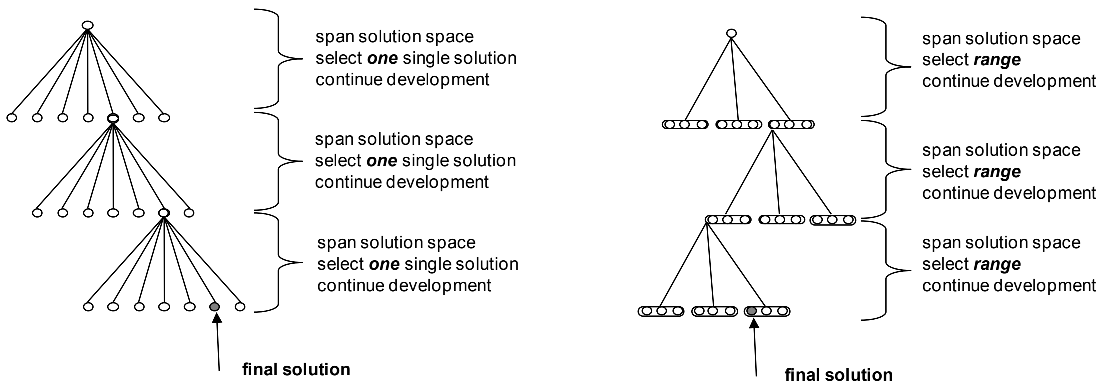


Figure 2-8 Traditional Product Development Process (left side, based on Andreasen 1987) compared to flexible product development (right side)

The application of set based design in the product development process is one way to enhance the flexibility during the development phase (Morgan & Liker 2006). Product requirements and characteristics are not precisely defined in the beginning, but rather as a range or a set. This range is narrowed further and further the better and more precisely the products can be defined in the process. Overlapping sets additionally restrict the solution space as only solutions (and requirements and characteristics) from the intersection of different sets are taken into account for further development.

Even though flexibility in product development has often led to successful results (as shown in Thomke 1997a) it has its downsides. According to Smith (2007) flexibility in product development should be applied for projects or project parts where uncertainty and change is likely to occur. However, having the possibility to accommodate changes can be misused by the stakeholders because process and system are now more tolerant of it. Smith (2007) explains the risk of development flexibility by the analogy to a high-performance motor-cycle: “it can get you to your destination quickly, but it can also get you into hospital quickly. To survive, you must ride your motorcycle with skill and wisdom.” Similarly, product developers and project managers have to handle flexibility with care in order not to run the project into chaos. Moreover, flexibility can be used as an excuse for indecisiveness, for not committing to decisions, or for reversing prior decisions. It can be used to justify the skipping of plans and emphasizing firefighting instead of a robust strategic planning and project execution, but “if you use flexibility as an excuse to be sloppy, you will derive no benefit from it” (Smith 2007).

2.4 Flexible Products

Besides strategic flexibility, manufacturing flexibility and enhancing the flexibility of the development process by using methods and tools in a specific way developing flexible products is another approach to increase the flexibility during the product development process. The underlying idea of flexible products is to transfer the definition given in Section 2.2.1 directly to the product:

> *Flexibility is the ability to adapt to changes easily and reversibly – while easily is understood as economically and rapidly and reversibly as changeably back to what it was before.*

This means that a product can easily be adapted to changes - during development processes and after product launch.

In order to support the approach of developing flexible products and to enhance the product’s flexibility various methods and tools can be applied. Existing approaches are discussed in Chapter 3, while in Chapter 4 a new approach is introduced.

To create a better access to the existing approaches and the new approach provided in this work and to support the understanding of the basic idea of flexible products, different definitions are presented and discussed in Section 2.4.1. Moreover a distinction is made between product flexibility and product robustness (see Section 2.4.2), the main purposes of product flexibility is highlighted (see Section 2.4.3), examples are given (see Section 2.4.4) and the measuring (see Section 2.4.5) and the trade-offs (see Section 2.4.6) of product flexibility are discussed.

2.4.1 **Definition of Flexible Products**

Research on flexibility in product development often refers to *flexible systems* (e.g. Saleh 2005). Hall (1962) defines a system as a set of objects, together with relationships between the objects and between their attributes; a single object can be understood as a system as well (Igenbergs 1993). Ulrich & Eppinger (2004) define a product as “something sold by an enterprise to its customers”. According to the given definition, there is hardly any difference between a system and a product. Thus, for this work both of the definitions of flexible products and flexible systems are used synonymously, by which *product* may be used even when the original work refers to *system*.

In Table 2-1 Palani Rajan et al. (2005) give paired examples of inflexible and flexible products. They state that “some products are clearly more flexible than others.“ These examples not only illustrate the concept of product flexibility, but also bring up several aspects that have to be considered when referring to product flexibility: Flexibility is best assessed in comparison of two or more similar products. It is difficult to discuss flexibility for a singular product or between vastly different products. Moreover “flexibility is highly dependent on the particular change in question” (Palani Rajan et al. 2005). For instance the screwdriver with removable bits is designed in anticipation of dimensional change (of screw).

Table 2-1 Examples of flexible and inflexible products (Palani Rajan et al. 2005)

Inflexible	Flexible
Old style screwdriver	New style with removable bits
Machine using custom-designed widgets	Lego machine
Wooden chair	Modern adjustable chair
Manual engine lathe	CNC lathe
Monolithic structural frame	Structural frame partitioned into sections

From a product analysis or comparison like this, general principles for product flexibility can be derived (Palani Rajan et al. 2003, Bischof et al. 2008). These principles can be e.g. the use of standardized parts and interfaces or the modularization of the product (more in Chapter 3 and Chapter 4).

Based on his axiomatic design theory (Suh 1990) Suh defines flexible products as products with time variant functional requirements (Suh 1998). Thus, the product has to be adapted to different functional requirements in the different phases of its life cycle.

Saleh et al. (2008) criticize this definition as it does not take into account the effort, time and costs that are necessary for adapting the product to the changed requirements. Moreover, it is focused on functional requirements only, completely neglecting structural requirements.

Roser & Kazmer (1999) extend Suh's definition by including time and cost to change a design to new requirements as a degree of the products' flexibility. The time and cost factor of adapting the product is a fundamental part of various definitions on product flexibility (e.g. Smith 2007, Thomke & Reinertsen 1998). Fricke et al. (2000) try to separate these two aspects, by defining *agility* as a product property that can be changed rapidly (time factor) and *flexibility* as a property of a product that can be changed easily, which more or less corresponds with the cost factor. In product development, time and costs are strongly related (Ehrlenspiel et al. 2005). There is a need for a definition of product flexibility to separate these highly linked parameters. The definition given by Saleh et al. (2001) describes flexibility as a product's property. It includes time as well as cost factors for adapting to changes in the product's environment: "…define flexibility of a design as the property of a system [or a product] that allows it to respond to changes in its initial objectives and requirements – both in terms of capabilities and attributes – occurring after the system [product] has been fielded, i.e., is in operation, in a timely and cost-effective way." This definition focuses only on the fielded product and excludes the flexibility of a product under development, which is the core of the work described in this thesis. Saleh et al. (2008) bring up the fact that flexible products "have been designed with certain characteristics; for example, additional design parameters, design margins, a particular architecture." These characteristics enable the (time and cost-efficient) adaption of the product to changing environments and requirements.

2.4.2 **Flexibility and Robustness**

Product flexibility is one way to handle changes in the product environment and uncertainty. Another way that strongly correlates with this approach is product robustness. Therefore product flexibility and product robustness have to be seen in pair, when use is made of a specific product design in order to handle changes.

Products can be understood as flexible when the adaption to changing environments is relatively easy – timely and cost-efficient. If there is no need to adapt a product, even if the environment has changed completely, then no time or costs are required, this would be the ultimate flexible product. Products that cannot and do not have to be adapted to external changes are also called *robust products* (e.g. Schulz et al. 2000). Sometimes it is argued that robustness is the opposite of flexibility (Pye 1978), while other researchers see robustness as the basis for flexible solutions (Chen & Lewis 1999). Even though distinctions and definitions vary widely, it is undeniable that flexibility and robustness strongly relate with each other. This interrelation is illustrated in Figure 2-9 below.

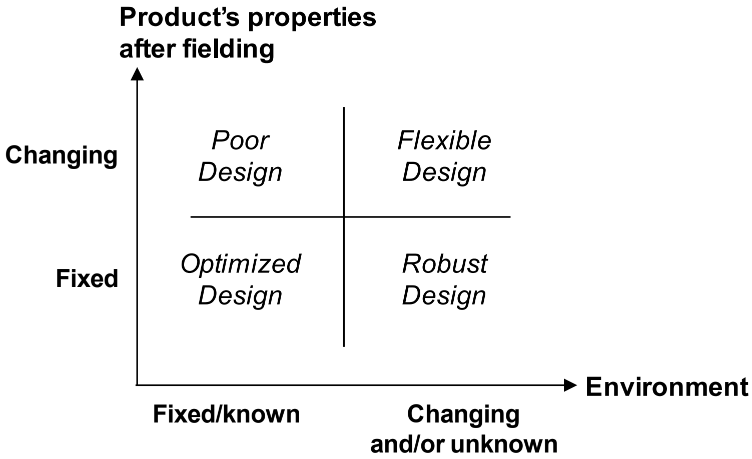


Figure 2-9 Flexibility and Robustness as a function of the product's characteristics and environment (based on Saleh et al. 2001)

Flexibility as well as robustness refers to the ability of a product to perform in different environments as a reactive way to cope with external changes. Mandelbaum (1978) defines these two abilities as state flexibility and action flexibility, respectively. While action flexibility is based on actively changing the product, state flexibility is understood as the capacity to continue functioning even in different or changed environments. Fricke (2006) explains robustness as the product's ability to absorb external changes within predefined tolerances, if possible without changing the product. This explanation, with the idea of predefined tolerances, is closely related to the origin of robustness in product development – robust manufacturing (Taguchi et al. 1989). This is illustrated by a simple example from Fricke (2006): When robustness is demanded the product developer can define a certain span of parameters instead of a precise value, "e.g. the signal can be handled from 4-7 Volts instead of only at exactly 6.5 Volts" (Fricke 2006).

Clausing (1994) interprets robust products in a slightly different way. Instead of maintaining functionality in a predefined range he announces that robust products function well even outside their preliminary application area. The products can be defined as minimal sensitive and/or maximal robust against changing environments at minimal costs.

Flexible products allow the adaption of their characteristics to new requirements after fielding. Robust products fulfill a fixed set of requirements; they handle changes without the need of redesigning or developing new products (see Section 3.2). Figure 2-10 illustrates the different concepts of flexibility and robustness for dealing with changing environments over time.

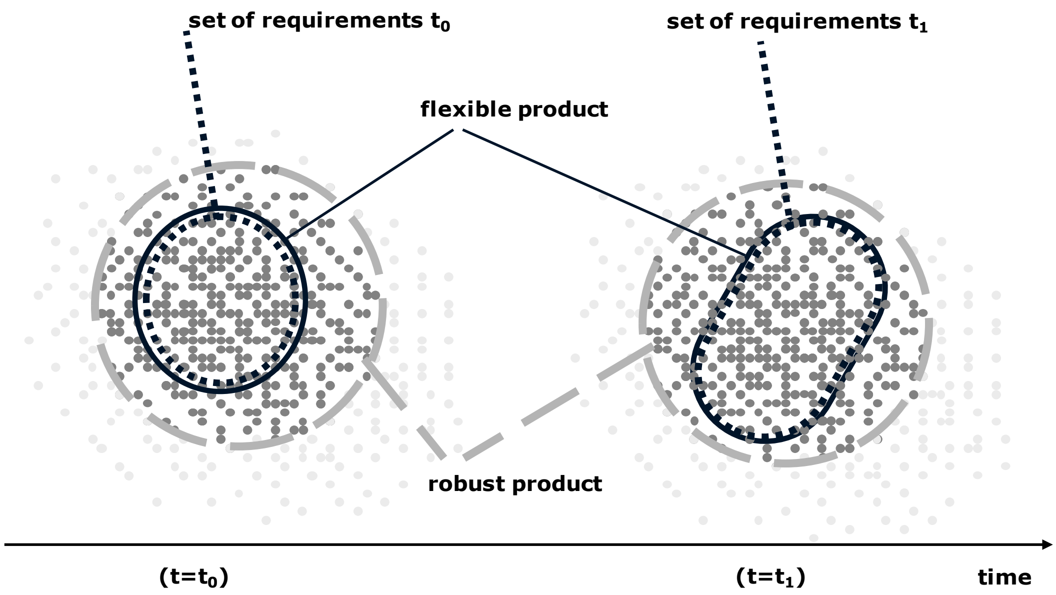


Figure 2-10 Model of flexible and robust products changing over time as reaction to changing environments

At a certain point of time (t_0) a specific set of requirements can be defined. These requirements have to be fulfilled by the product to satisfy the customers. A flexible product fulfills the requirements more or less directly, while a robust product does not only fulfill the specific set of requirements, but a much wider range. The specific set of requirements that needs to be fulfilled changes over time. At a second point in time (t_1) other requirements have to be covered by the product. The flexible product can (easily) be adapted to the new set of requirements - more or less fulfilling the new requirements. The robust product does not need to be changed, still fulfilling the same requirements, including the new set.

Saleh et al. (2001) explain the two concepts of flexibility and robustness in one perspicuous example: a spacecraft with an expected life-time of 50-100 years is faced with two major challenges. First, robustness has to be designed into the spacecraft in order to maintain on-board functionalities after launch. Second, flexibility is needed in order to "create new functionalities on-board, for changes in requirements occurring after launch, as events unfold, new environments are explored and/or new data becomes available, etc." (Saleh et al. 2001).

The concept of robustness can also be interpreted as *universality*. Saleh et al. (2001) refer to software development, where flexible software is understood similarly to flexible products as easily changeable in a timely and cost-efficient way. In contrast universal software can be used in a variety of situations without change or modification, which parallels the definition of robust products.

In conclusion, flexible and robust products do not have to be considered contrary, as both concepts aim at the same goal. With this in mind, for this work they are defined as follows:

Flexible products can be adapted to changes easily and reversibly – while easily is understood as economically and rapidly and reversibly as changeably back to what it was before.

Robust products cope with changes in the product environment without any necessary adaption.

It has to be acknowledged that the two approaches of developing either flexible or robust products to handle changes legitimately coexist despite their same purpose. Flexibility as well as robustness does not only provide benefits during developing, but come with trade-offs that have to be taken into account carefully, when applying either of the approaches. Considering only one of the two approaches might not be the best solution, when developing in changing and uncertain environments.

2.4.3 **Purpose of Product Flexibility**

One purpose of developing flexible products is to offer flexible products to the customer. This kind of flexibility is not the scope of this work, but it is maybe the most obvious one. The flexibility can be upon the request of the customer or it can be offered by the company without specific request in order to offer a product of higher value to the customer.

A flexible product can better match the requirements, especially after fielding, when it can be adapted to the changing requirement, while traditionally designed products cannot. This capability to adapt to changes after the fielding of the product can be beneficial as well to the customer as well as to the company.

As a third purpose product flexibility can also be demanded by the company in order to create a greater product variety (Saleh et al. 2001). Instead of developing different products for different customers, one or more flexible products are developed that can be adapted to the different customer requirements and thus cover a wide range. This idea is illustrated in Figure 2-11. It has to be taken into account that the flexibility of these kinds of products can only be used up to a certain point in the development process. Later on decisions are made that reduce the product flexibility. E.g. in automotive industry the platform of a car can be considered flexible (if various different cars can be build on its basis), but the finished car is not necessarily flexible.

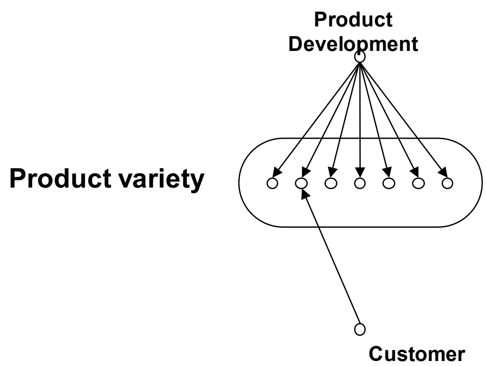


Figure 2-11 Product variety derived by product flexibility as benefit for the customer

Inasiti (1995) has shown that product flexibility can also be beneficial during product development and not only after fielding, e.g. by saving resources *during* development. In Figure 2-12 Thomke & Reinertsen (1998) illustrate that a flexible product approach can drastically accelerate a development project and consume less resources; in comparison to the traditional approach the development of flexible products is significantly faster for low volume products (Thomke & Reinertsen 1998).

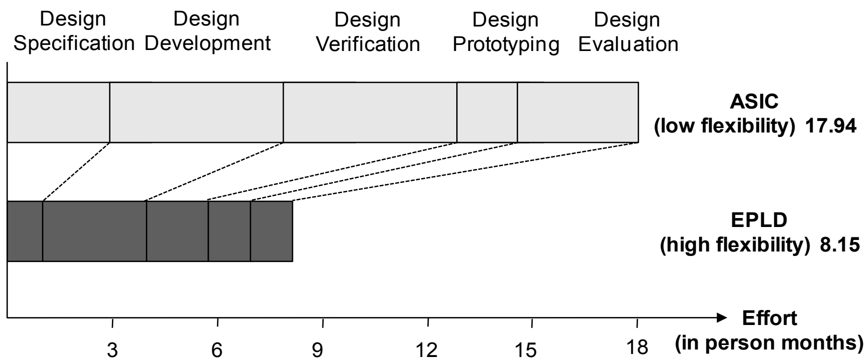


Figure 2-12 Distribution of (software-) development effort (Thomke & Reinertsen 1998)

Moreover flexible products are being developed to derive the general benefits of flexibility mentioned in Section 2.2.2: to handle complexity, reduce cost of changes, reduce technical risks and delay decisions. Another purpose of implementing flexibility in the product design is to avoid the need of changes on the product entirely, because design commitments can be made very late (Thomke & Reinertsen 1998). Time consuming information gathering activities in the early phases of the development process are made obsolete by the flexible product design approach.

Table 2-2 Purposes of developing flexible products

purpose	specific purpose	product example
benefit from flexibility during product development	handle changes handle uncertainty handle complexity safe resources accelerate process	the bioreactor project (see explanation on the follwoing pages)
enhance product flexibility	create a product of higher value for the customer	Kitchen Aid kitchen machine
create higher variety	better matching customer requirements by offering various similar products	platform based cars
allow eased adaption to changes	ease adaption after fielding	IKEA shelf system

Besides product flexibility product robustness is another way to handle changes in the product environment. There are two specific purposes behind this approach. The first is to develop a product, which can be used in various environments. In general these different environments are known up-front, so that all requirements from the different sites of operations can be derived in the beginning of the development process. The product can be developed in respect to all possible (future) requirements, thus making it a robust product.

A second purpose of developing robust products is to make them long lasting despite uncertainty about future changes within the product environment. This can e.g. be achieved with help of specific methods, like scenario analysis, in order to detect possible future requirements or by "exaggerating" present requirements, as they often tend to become tightened in the later product life.

Table 2-3 Purposes of developing robust products

purpose	specific purpose	product example
enhance product robustness	prepare product for various environments	touring bike
enhance product robustness	make product long-lasting despite environmental changes	office binder

2.4.4 **Examples of Flexible and Robust Products**

Following, examples for flexible products are presented in order to provide a clear idea of the underlying concept. In Table 2-1 Palani Rajan et al. (2005) provided several examples of products that are relatively more flexible than others. They state that it is rather difficult to assess product flexibility for a single product. Here single products are chosen in order to explain, what in particular makes the products flexible, robust respectively. As the description is about the quality of flexibility and robustness instead of the quantity it is not necessary to make direct comparisons between two similar products.

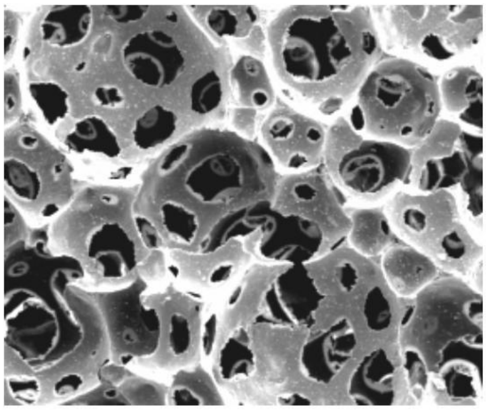
Bioreactor Project

The first example of a flexible product is developed with a flexible design mainly in order to benefit from its flexibility already during the development process.

The research described in this dissertation was embedded in an innovative bioreactor project, in which mammalian cells are cultivated in aluminum oxide foam structures. The microscopic structure of these foams can be adjusted by varying the process parameters. It is possible to create a microscopic structure similar to the human bone. This foam has millions of permeable compartments with a diameter of about 100 nm. This environment is promising for the cultivation of adherently growing cells. Within the project mammalian cells were chosen to research the possibilities of cell cultivation in ceramic foam structures (Goralczyk et al. 2009).

Figure 2-13 (a) shows the ceramic cylinders, which were used for the cultivation of the cells. Various sizes were tested; the best compromise of manufacturability, handling and nutrition supply were cylinders with a diameter of 10 mm and a length of 10 mm as well (right one on the photo). Figure 2-13 (b) shows a scanning electron microscope (SEM) picture of the pores within the foam with a diameter of about 100nm.

(a)



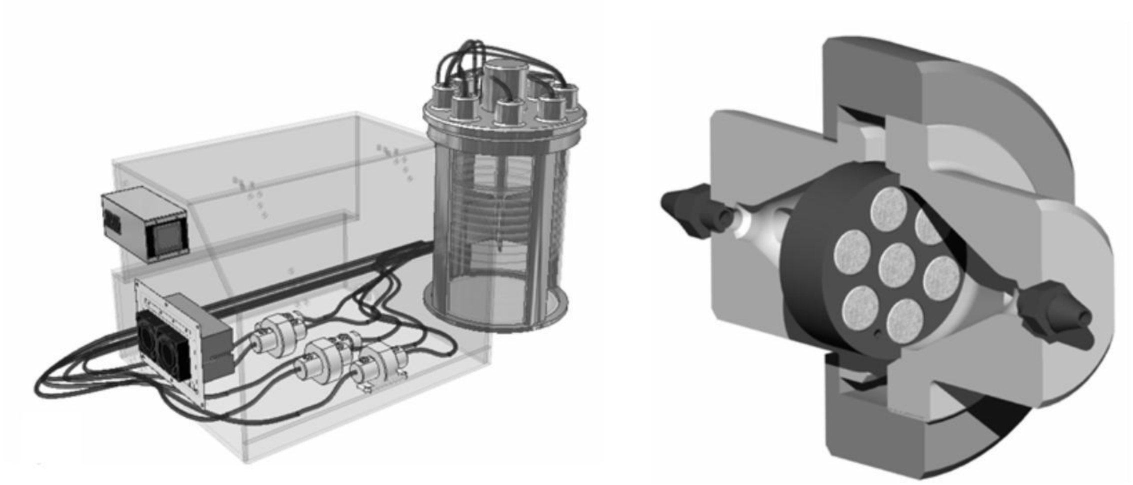
(b)

Figure 2-13 Aluminium oxide foams

The engineering design task of this project was to develop a device, a bioreactor, in which the ceramic foams with the cell can be placed. The bioreactor is used to create an adequate atmosphere for the cells. This means that the cells have to be supplied with culture medium, oxygen, the right temperature, the right pH-value, and be protected from mechanical stress.

In the beginning of the project it was not clear if the cells will grow in the foam; in this fundamental research project many parameters were unknown and uncertain. This is often the case in innovative projects. Parameters related to the cells (e.g. nutrition supply) were likely to change. Thus, the bioreactor project is a good example of a development project in the context of changing environments as described in Section 2.1.1.

Figure 2-14 illustrates the bioreactor: Figure 2-14 (a) shows the whole reactor system, in which the different modules were integrated. Figure 2-14 (b) is a sectional view of one of the modules, which contains 7 of the ceramic cylinders, in which the mammalian cells are cultivated.



(a) **(b)**

Figure 2-14 Flexible bioreactor for cell cultivation

The project was used to implement the approach of flexible design in order to evaluate its usefulness for handling changes. Attempts were made to develop a flexible reactor from the beginning, so that later changes, for example due to test results, can be implemented easily. In the beginning of the development project a few standardized interfaces between the parts and modules[6] of the reactor were defined, as suggested by Palani Raja et al. (2003) in order to enhance the flexibility of the reactor. Later in the project these interfaces could be used for various different purposes like connecting measuring devices, allowing extracting samples and providing visual

[6] For definition of *module* see Section 3.3

access to the cell nutrition supply. This way the bioreactor could handle different requirements without any adaption or redesign.

Due to the participation of the design researcher in the project direct feedback could be derived. However, the setting has two major handicaps: First, theoretical feedback on flexibility and flexible design start at the same time as the development of the bioreactor. Thus, it is challenging to implement the new findings in the actual design. Second, the research and the application of the newly derived findings are done by the same person. Thus, like in most participant observation (Blessing & Chakrabarti 2009) projects, the results are strongly biased. According to the standards of natural science with its analytical and empirical techniques, these observations are insufficient to draw general conclusions (Popper 1972).

Even though the conclusions cannot be used to validate the approach of flexible design subjectively the approach of developing products with a flexible design has led to good results. The developer felt more secure. Decisions could be made with low risk, but without the necessity of procrastination.

Kitchen Aid Kitchen Machine

The following example of a product that can be considered flexible is shown in Figure 2-15. The kitchen machine (KitchenAid 2009) can be used to handle a great variety of tasks related to cooking. By using different add-ons, the same machine can, for example, be transformed from a fruit press to a vegetable cutter or a mixer. The switch from one purpose to another can be handled fast, reversibly and without any tools, thus easily. However, one downside is that the flexibility offered by this product is limited to predefined functions, which are represented by the various kinds of add-ons.

Figure 2-15 Flexible kitchen machine (Kitchen Aid 2009)

Volkswagen Platform Design

Another purpose of product flexibility mentioned in Section 2.4.3 is to enhance the product variety so that the customers can choose from a range of similar products the one that best fulfills their requirements. A nice example is the platform design in automotive industry: Instead of developing one car that hopefully fulfils the requirements of many different customers (e.g. the original Volkswagen Beetle) automotive companies build a whole series of different cars on the same platform. Figure 2-16 illustrates that Volkswagen is able to offer twelve rather different cars to the customer. The customers can choose individually, which car best fulfils their personal requirements. Moreover the customers can choose among various different engines and specific extras to individualize their cars so that hardly two cars are absolutely identical. A downside of the platform approach is the higher effort necessary to initially develop a good platform design. Moreover it can lead to brand image loss by selling a premium brand sports car (Audi TT) based on the same platform as an economically priced saloon car (Škoda Octavia).

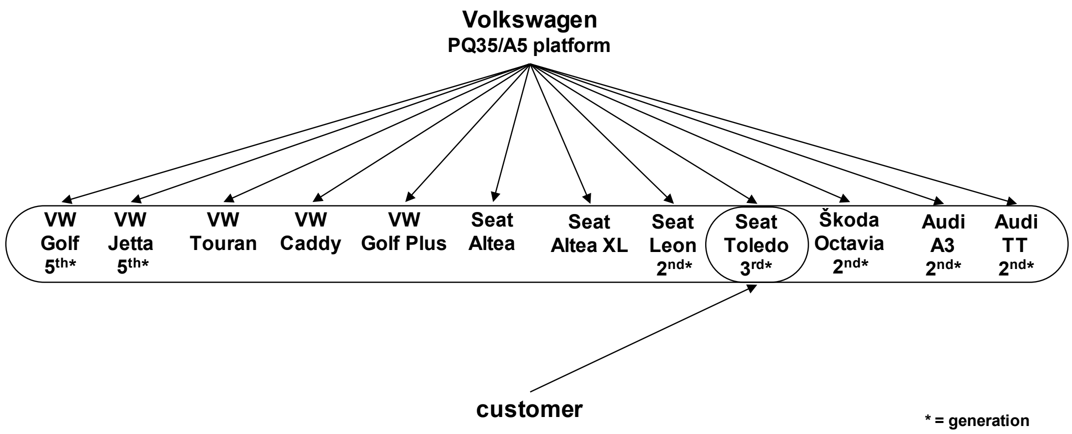


Figure 2-16 Variety of twelve different cars based on Volkswagen PQ35/A5 platform

IKEA Shelf System

Figure 2-17 shows a shelf system from IKEA (2009). It can be considered as a building set (Pahl & Beitz et al. 2007, see Section 3.3), which can be extended unlimitedly. Special parts allow adding new functionalities beyond the original purpose of a shelf - e.g. by adding a table top and drawers. Due to a high number of interfaces, holes in which pins are plugged, the boards of the shelf can be adjusted easily to different heights. Readjusting can be carried out without any tools. Thus adapting the shelf to a specific environment (e.g. a private library where the height is adjusted to books, or an office environment where the shelf is used to store binders) is easy. The shelf can hence be considered flexible according to the definition given in Section 2.4.2. It represents the purpose of changing the product after fielding to specific and/or changed environments. As a disadvantage of this flexibility the customer has to stick to this specific shelf system. Flexibly combining one shelf system with another one from another manufacturer is hardly possible. Moreover some customers might rate the visible interfaces (holes) as an aesthetic downside.

Figure 2-17 Flexible shelf system (IKEA 2009)

Touring Bike

The Kona touring bike shown in Figure 2-18 can be considered to be robust in the traditional mechanical way (e.g. handling heavy loads and long term- and dynamic stress) as well as robust and flexible in sense of handling changes in the products environment.

The steel frame allows for eventual maintenance-welding on a world tour, as steel welding is common almost everywhere. The racks and various interfaces for fenders or additional racks make the bike easy to adjust to specific purposes and environments. Thus, the same bike can easily be used for inner city commuting as well as for adventurous travelling on the Silk Road. However, the provided flexibility is limited and a flexible bike design like this has its trade-offs (see Section 2.4.6), e.g. compromising comfort in comparison to a fully suspended bike or reduced pedal efficiency in comparison to an optimized road race bike.

Figure 2-18 Flexible/robust bike (Kona 2009)

Office Binder

The office environment has changed dramatically over the last decades. In the last century typewriters, telephones and electric calculators revolutionized office work; obviously the implementation of computers had the biggest impact on the work. However, despite this fundamental change of the office environment some office equipment has remained almost unchanged over the decades. Figure 2-19 shows a classical binder as it can be found in almost every office today. This product survived in a dramatically changed environment without undergoing any changes itself. Thus, it is an example of a robust product being able to cope with a changing environment. However, this robust product can only handle limited change on its initial requirements. If, for instance, the paper format would be changed to a big square format, new binders had to be designed.

Figure 2-19 Robust office binder (Leitz 2009)

The examples above reveal the concept of flexible and robust products coping with changes. These everyday examples not only show the wide spectrum the approach of product flexibility is able to cover, but also demonstrate how far it is integrated into our day-to-day environment. These product examples also show that “flexibility is not a free good” (Stigler 1939). Flexible products always come with trade-offs. These trade-offs are more closely examined in Section 2.4.6.

2.4.5 Measuring Product Flexibility

Measuring product flexibility is challenging. Thus, measuring is best done in comparison with two or more products. This is analog to other Design for X (DfX) approaches, as for example the Design for Lightweight approach: Even though absolute measures of weight, for example of a car, are easy to get, if a car is lightweight can only be seen in comparison to other cars. The other challenge of measuring the flexibility is the strong correlation with the expected changes. The expected changes to be handled by the products are a prediction. They can be wrong and thus be misleading for the measurement of flexibility. Figure 2-20 is an example of a relatively flexible product (b) and its less flexible counterpart (a), given by Van Wie (2002). According to him and his definition of flexibility, the modern office chair is more flexible than the wooden chair. This also corresponds with the definition of this work.

(a) **(b)**

Figure 2-20 Examples of inflexible (a) and flexible (b) products (based on Van Wie 2002)

Palani Rajan et al. (2003) provide a method for handling the difficult task of measuring product flexibility. Its main tool is the Change Mode and Effects Analysis (CMEA). Analog to the Failure Mode and Effects Analysis (FMEA, e.g. Stamatis 2003) a table has to be filled with Potential changes, Potential Effects of change, Design Flexibility, Potential causes of change, Occurrence and Readiness, for each part and module of the product. The CMEA delivers three results:

First output is the Design Flexibility of the product for a specific possible future change. This helps the developer to have an in-depth look at particular kinds of changes.

Second output is the overall flexibility of the product. This includes the “Readiness” of the company and the product developers’ preparedness for changes and redesigning the product.

Third output of the CMEA is the Change Potential Number (CPN), which indicates the overall flexibility of the product for any kind of future change (Palani Rajan et al. 2003).

As an additional output they highlight the systematic documentation of possible future changes and effects. Even though they show some impressive applications, the method has its downsides: The main source of input data is customer feedback from the fielded product. Thus, the method is only applicable when the product is fielded or if usable feedback can be accomplished in another way. Products under development are hard or even impossible to measure. Like the FMEA the CMEA works best for experienced developers.

Methods proposed by management science are also hard to apply, especially during the development; e.g. Mandelbau & Buzacott (1990) state that the flexibility can be measured by the number of remaining alternatives. The more alternatives remain after a first commitment the higher the flexibility (of the product) is. Gupta & Rosenhead (1968) propose a similar measure of flexibility. In their opinion flexibility (of a decision) “must be measured in terms of the number of end states which remain as open options [after a first decision is made].“

De Neufville (2002) argues that many models for calculating (the value of) flexibility are derived from financial options. They are not suitable for real options or other contexts e.g. product development. Saleh et al. (2008) point out that it is useless to define an absolute measure of a product without considering its context. In their opinion, the measurement of flexibility always has to include, in what respect the product is flexible. If a product is designed with a flexibly design in order to cope with uncertainty, it has to be declared what kind of uncertainty it is able to deal with or the range of output it delivers.

When trying to measure the flexibility of products many researchers forget to mention the fact that high flexibility is not always the most desirable feature. Flexibility has its trade-offs that are explained in Section 2.4.6. Flexibility has to be seen more as an option than an obligation when developing products. Whether a method to measure product flexibility can be applied or not, the developers have to decide if higher flexibility is the better approach for every product. Maybe common sense, experience and “constructive Gefühl” (Reuleaux 1861) or “Feel for Design” as described by Hubka (1975) remain the best tools for deciding to which degree a product has to be flexible.

2.4.6 Trade-offs of Flexible Products

The most important trade-offs of product flexibility are on costs and functionality: Saleh et al. 2008 conclude that "it is likely that flexibility can only be obtained through performance and/or cost penalties", highlighting the importance of balancing these trade-offs carefully against the benefits and additional value provided by flexibility.

Fricke (2006) explains that flexible products usually have higher initial costs compared to traditionally developed products. Possible benefits in respect of costs can only be expected in the later phases when changes occur. It is most probable to derive these benefits after product fielding, when the development of next generation follow up products is eased (Figure 2-21). The more changes occur, to which the product has to be adapted to, the higher is the probability to benefit from the flexible product.

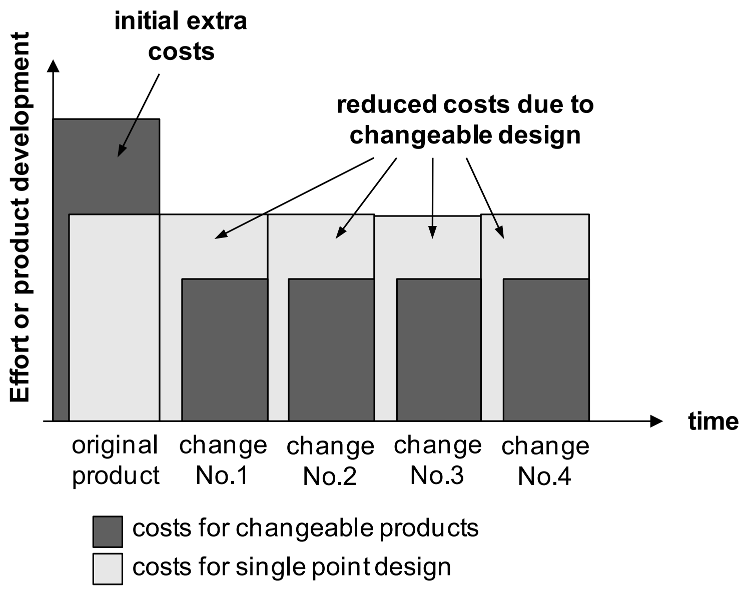


Figure 2-21 Qualitative cost reduction based on flexible products (Fricke 2006)

Developing flexible products can ultimately be cheaper (and faster) in a fast changing environment. However, Thomke & Reinertsen (1998) reference that for high volume products designing more simple and less flexible products might be the more economic approach.

Besides cost and performance compromises various researchers additionally highlight the following downsides of product flexibility (Norman 1999):

- Flexibility can lead to unnecessary change, because the product is more tolerant to it.
- Flexibility can lead to chaos in the whole development process.
- Flexibility can lead to sloppiness of working on the tasks in product development.
- Flexibility can lead to skipping decisions about product characteristics and manufacturing.

- Customers may ask for more/faster changes if they are aware of higher product flexibility.
- Flexibility can be a crutch for indecisiveness.
- Flexibility can be used as an excuse.
- Flexibility can reduce usability.

All these downsides and trade-offs can be balanced against the benefits of flexibility. Figure 2-22 qualitatively shows the degree of flexibility over costs. Similar qualitative graphs can be generated for the other trade-offs as well, like functionality or product weight. For the total costs (sum of cost of flexibility and cost of changes) Fricke & Schulz (2005) suggest that there is an optimal degree of flexibility, where costs are at minimum.

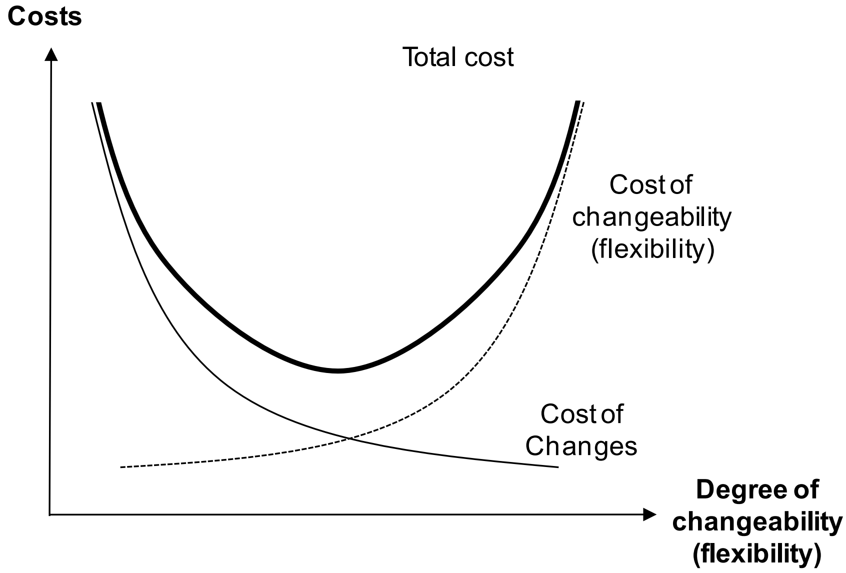


Figure 2-22 Degree of flexibility vs. sources of cost, (based on Fricke & Schulz 2005; Malmström & Malmqvist 1998, Smith 2007)

Ahmed et al. (2003) researched how designers approach design tasks. They found that especially experienced designers are aware of trade-offs and limitations. Thus, they are capable of making good decisions based on compromises. Hence, product developers should be able to trade-off the benefits of product flexibility with its disadvantages and thus develop the product with a reasonable degree of flexibility.

2.5 Summary and Discussion

The context of uncertain and changing environments is well recognized in academia as well as in industrial practice. The reasons for both uncertainty and changing environments are manifold and cannot be neglected in product development. It is hardly possible to remedy the reasons directly. Even handling the effects of uncertainty and changing environments is not a solved challenge yet. The various proposed concepts are far from being mature solutions. Simple solutions like "doing it right the first time" do not work in reality. Till now it is not even possible to tell how serious the effects of changes during the development phase are. There are serious doubts about general estimates like the well known "rule of ten".

However, flexibility is often a proposed approach to handle uncertainty and changes in the product, as it has proven great potential. Admittedly flexibility is seldom initially implemented in either the product development process or the product itself. Only in retrospect flexibility has been detected as being pivotal for the success of various development projects.

Despite the recognition of the great potential of flexibility in product development – especially in uncertain and changing environments – the whole concept of flexibility is not very elaborated. This can be recognized by numerous definitions on flexibility, which are partly contrary, often imprecise and naïve (Sethi & Sethi 1990). Therefore a new definition is given in this work. This is not only to unify the understanding of this specific research, but in order to formulate a better basis for the general understanding of flexibility:

> *Flexibility is the ability to adapt to changes easily and reversibly – while easily is understood as economically and rapidly and reversibly as changeably back to what it was before.*

A lot of research on flexibility in product development context is about managerial and strategic flexibility. Other foci are manufacturing flexibility and flexibilizing the product developing itself by either applying specific methods, tools and carrying out flexible processes or by interpreting existing methods and processes more freely and thus enhance the flexibility of product development. Developing flexible and robust products is another approach to derive benefits from flexibility for the whole product development process.

This approach, however, is the least analyzed one. Thus, definitions on flexible products are also vague and hardly useful for either design science or product development practice. One reason for this is that most definitions (and most research behind them) do not take into account the strong correlation of product flexibility and product robustness as described by Saleh et al. (2008). They explain that either robustness or flexibility of a product is a valid approach for handling changes in product development. Flexibility is understood as the capability to easily adapt or be adapted to external changes, while robustness means that the product does not have to be changed, because it still functions properly despite a changed product environment. Taking into account this important aspect a new definition of product flexibility is given in this work:

Flexible products can be adapted to changes easily and reversibly – while easily is understood as economically and rapidly and reversibly as changeably back to what it was before.

Robust products cope with changes in the product environment without any necessary adaption.

This kind of product flexibility and robustness is explained with six product examples. Together they represent the wide area of application for flexibility as well as for robustness. Each product described in the examples was developed flexible or robust for a different purpose: The kitchen machine is flexible in order to offer a product of higher flexibility to the customers when the *product is fielded*, so that they can directly benefit from it and are willing to pay for a product of higher value. In contrast the bioreactor was developed flexible specifically in order to cope with uncertain requirements and changes *during* the development process.

The benefits derived from flexibility during the development process as well as those that occur later in product life do not come without trade-offs. Among these trade-offs are for example the risk of sloppiness and chaos in the development of the product or a reduced usability of the product. However, former research indicates that (experienced) product developers are aware of trade-offs and limitations and that they are able to handle them.

The approach of developing either flexible or robust products to handle uncertain and changing environments is considered having great potential, while the trade-offs of this approach are perceived as manageable. However, it remains the following question for the next chapter:

How can products specifically be developed to achieve either high product flexibility or high robustness?

3 APPROACHES FOR DEVELOPING FLEXIBLE PRODUCTS

Products provide value through their ability to fulfill the customers' requirements. These change over time and new ones emerge. Various approaches in product development exist, which all aim in one way or another to fulfill the customers' requirements. All these approaches can be described with three basic paradigms. First, several approaches aim at easily creating a great variety of products. Customers can choose, which product best matches their personal requirements. The second paradigm is to develop robust or universal products. These kinds of products try to fulfill a great variety of different requirements. Thus, one product can be used to match the different requirements of a wide range of customers. The product does not have to be modified or adapted for this purpose. The third paradigm is to develop products that can easily be adapted to the specific requirements of each customer or of each cluster of customers respectively.

Not all product development approaches can be allocated clearly and exclusively to one of these three paradigms. E.g. mass customization aims at exactly matching every customer's requirements, but it makes use of easy product modification. Some of the analyzed approaches focus on the aim, e.g. create a variety; various tools are proposed to achieve this aim. In contrast other approaches are means oriented. They propose specific means, like platform design; the aims of the specific means applications are often not explicitly described.

In this chapter the approaches are clustered in eight groups. Several approaches fit into more than one group. They are allocated where they are considered to fit best. The eight groups should be understood as a proposal to help getting an overview. It cannot be interpreted as a rigid scheme. Concepts and development approaches, which do not fit into one of the eight groups at all, are listed in the last section on miscellaneous approaches. This third chapter concludes with a summary and a brief discussion of the diverse approaches.

3.1 Designing Optimized Products

Definition and Purpose

According to Simon (1987) the optimal choice (or product) is determined as the 'best' out of a set of alternatives and a given set of constraints. Thus, optimizing is understood as choosing the best available alternative according to one or more criteria. In contrast, satisficing is understood as meeting or exceeding specified criteria, but without guaranteeing that the solution is either the optimum or in any sense the best. The difference is "between looking for the sharpest needle in a haystack" (optimizing) and "looking for a needle sharp enough to sew with" (satisficing) (Simon 1987). "Optimisation and satisficing are not competing theories of choice. A process of satisficing can always be converted into an optimisation problem by modifying the latter's objective function and including in it the cost of the search" (Saleh et al. 2008).

Optimized products are sensitive to environmental changes (Saleh 2001). Figure 3-1 illustrates that for optimized products (μ_{opt}) changes on design variable by Δx lead to a large variation Δp in the performance. Contrarily the same variation Δx of the design variable has no influence on the performance of a robust product (μ_{robust}; see Section 3.2).

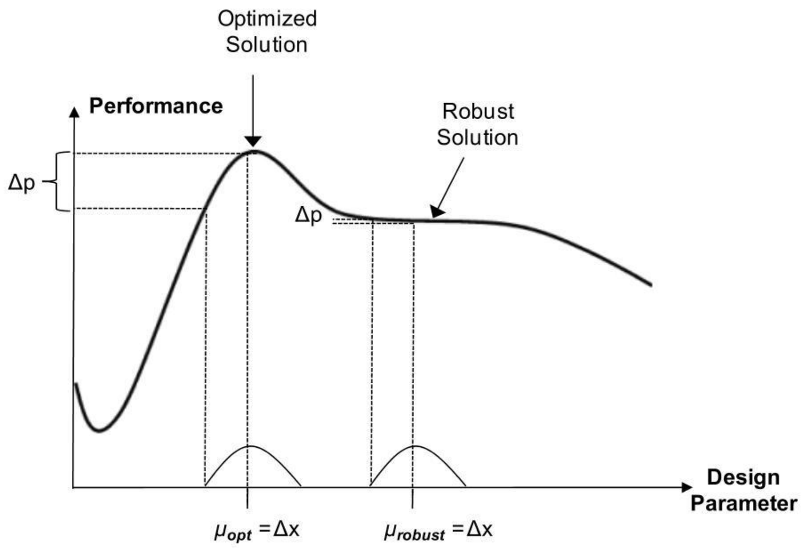


Figure 3-1 Robust design: Variation of the design parameter around μ_{opt} causes greater variation in the performance than when the design parameter is set to μ_{robust} (based on Saleh et al. 2001)

This sensitivity of optimized products is recognized as a disadvantage (Saleh et al. 2001), while product flexibility is often highlighted as a benefit (e.g. Smith 2007). Product flexibility eases changing of the design parameters, to adapt the product (optimize) to required changes in performance, i.e. finding the new optimum when constraints have changed. Thus the flexibility can be helpful for the optimizing process. This phenomenon can be understood the other way around as well. Instead of interpreting the optimized product's sensitivity as negative, it can also be considered as flexible: A great variation in performance (e.g. for product families) can be derived easily with little variation in the design parameter once an optimal product is developed.

Origin and Examples

Optimized products can be found in almost any branch of the product development industry. They are especially present when regulations, requirements and conditions are well known, precisely defined and strict. This can for example be found in various sports such as athletics, motorsports, cycling and golf. Professionals use a variety of individually optimized products, influenced not only by the regulations and the athlete's requirements, but also by the specific event, e.g. the completion track and weather conditions. Optimized products are also common in branches where one-of-a-kind products are common, e.g. aerospace and space industry (Saleh et al. 2001).

Support

Finding the right design parameters in order to obtain the optimized solution is supported by various methods and tools such as calculations (Nilchiani & Hastings 2004), tests and experiments (e.g. Thomke 2003), computer simulations (e.g. Laporte & LeTallec 2002) and specific methods like Kaizen (Laraia et al. 1999). These tools and methods make use of two different approaches to finding the optimal product. The first is to develop and set up a (material) product and variegate the design parameters later until optimal performance is achieved. The second approach is to directly attain the optimal parameters before a material product is build instead of developing, testing for optimal parameters and then redeveloping and rebuilding it with these parameters. Achieving this goal is for example supported by the calculation methods. Both approaches can also be combined through an iterative process.

Dis-/Advantages

Optimized products make good use of resources; their efficiency is high. They perfectly match the customer requirements. In changing environment, however, they are optimized only for a limited period. Without readjustment or adaptation they can lose their optimized status and can perform even worse than (initially inferior) robust products that maintain their performance for a wider interval of external changes.

Highly optimized products are usually one-of-a-kind or low volume products. The development process is characterized by numerous time and cost intensive iterations. Thus, optimized products are often expensive. Moreover product optimization might lead to less flexibility (Adler et al. 1999). However, optimized products perform best. Even in changing environments there is the possibility of outperforming robust (or non-specified) products. Due to this and due to the link between optimized products' sensitivity and flexibility, optimization should be considered when developing for changing environments. Optimization and optimization methods can be applied either to enhance product flexibility or to set the product's performance level so high for the initial status that even if strongly affected and reduced by changes in the product environment the product performs sufficiently.

3.2 Designing Robust Products

Definition and Purpose

Robust Design is a design methodology developed in order to make products' performance insensitive to raw material variation, manufacturing variability and variations in the operating environment (Saleh et al. 2001, Phadke 1989). It was developed in the late 1950s by Taguchi (1987) and builds upon ideas from statistical experimental design (Saleh et al. 2001). Haberfellner & de Weck (2005) define robustness as the "ability to perform under a variety of circumstances; ability to deliver desired functions in spite of changes in the environment or internal variations." (see Section 2.4.2). In other words, robustness implies de-sensitizing the product's performance characteristics and properties to changes (or noise factors) in the product environment or within the product. Ku (1995) describes this insensitiveness to changes as "a resistance or immunity to change". Fricke (2006) explains the idea of Robust Design as damping external influences on the product (performance) and thus increase its reliability. According to Saleh et al. (2001) the three most common influences and changes a robust product has to deal with are variation in condition of use, deterioration or variation with time and use and finally production and manufacturing variations.

Origin

Robust Design in product development is derived from production engineering (Taguchi 1987, Saleh et al. 2001). Here production was improved not by narrowing tolerances and increasing performance, but by reducing the negative effect of variation. This positive property is now implemented in various products from a wide range of branches (Jiao & Tseng 2004) as for instance in automotive industry. The customers want a car "that will start readily in northern Canada in winter and not overheat in southern Arizona in the summer (…). In other words, (…) [they want] a car that is robust with respect to variations of use conditions. (…) [They also prefer] a car that is as good at 50 000 miles as when new, that is robust against time and wear [Phadke 1989]" (Saleh et al. 2001).

Support

External changes can only be handled within predefined tolerances (Fricke 2006). However, Clausing (1994) explains that a robust designed product functions well even outside its preliminary application area. Therefore the main aim of the Robust Design approach is to find the optimal set of design parameters, so that the product can be defined as minimal sensitive and/or maximal robust for a changing environment at minimal costs. Figure 3-1 illustrates that for a robust product (μ_{robust}) the product's performance remains the same even for a great variation of Δx of the design parameter. The product's design parameters can be calculated directly to insensitivity against external changes.

Moreover sticking to standard designs and implementing an early "design freeze" (Eger et al. 2005) can help to avoid internal changes during the development. Hence, the design freeze enhances the products robustness in this phase of the product life. Aside from this, anticipation of future environments is important when developing products for robustness. Various methods support this step (e.g. Pahl & Beitz et al. 2007). Developing robust products often leads to over-engineering and vice versa (Bischof et al. 2008). Over-engineering is often suggested for uncertainty and changing environments (Palani Rajan et al. 2003). This over-engineering is not limited to forces, stress and power, but can and must also be applied for other requirements and conditions. In order to develop robust products requirements have to be exaggerated. Additional functions have to be implemented in the beginning. This can lead to rather long lasting products. E.g. the "Spirit Mars Mission" was initially planned for 90 days only. Due to the robustness of the "Mars Rover" the mission could be extended to over five years and is still ongoing (NASA 2009).

Dis-/Advantages

Robust design has several advantages for the product developer as well as for the product user. First of all, the robust product can be used in different environments. Even if the initial environment and product requirements change, the product retains its functionality. Thus robust products tend to have a longer lifetime and respectively a longer use phase. This can provide a higher value to the customer. In contrast to optimized products, robust products are often designed as One-fits-many, e.g. the same car for northern Canadians as for people living in south Arizona, rather than one-of-a-kind products. However, there are several exceptions, like highly unique spacecrafts (Saleh et al. 2001). This reduces the effort of developing several different products to satisfy all customers. Thus, costs are reduced and more effort can be put on the one robust product. This can lead to higher quality.

Besides offering several advantages Robust Design has its trade-offs. Usually the products perform inferior to optimized products at least for a certain period of time (see Figure 3-1). They are not optimized to each customer's specific requirements. Hence they are more often a compromise not fully matching the requirements. Moreover, even if there are theoretical options of cost reduction, robust products can be more expensive. This can, amongst other reasons, be explained by the higher development costs required for the high effort necessary to find and define the design parameters for optimal robustness.

Fricke (2006) points out that Robust Design does not necessarily have to be implemented for the whole product. Benefits can already be derived if applied only for single modules, parts and subsystems. This way robustness not only helps to handle uncertainty and changing environments directly, but also supports Design for Flexibility (see Section 3.4) where robustness is used to specifically reduce internal influences from one product part on the other (Palani Rajan et al. 2003).

3.3 Modular Design – Design for Modularization

Definition and Purpose

In the Cambridge Advanced Learner's Dictionary (2007) a module is defined as: “one of a set of separate parts which, when combined, form a complete whole.” More related to product development, Pahl & Beitz et al. (2007) define a module similarly as a functional and physical object, which is relatively independent from the other product modules. Numerous similar definitions can be found (e.g. Erixon 1998). Like Mikkola & Gassmann (2003, 3.6) Eppinger et al. (2000) compare modular products to integrated ones: “A modular system is one whose sub-functions can be abstracted into sub-systems, and whose resulting sub-systems and modules interact via interface, only requiring a minimum of information. An integrative system is one in which such modularization is not possible.” Others especially point out that the modules are connected via “well-defined interfaces” (e.g. Hölttä-Otto 2005). Blackenfelt (2001) gives a comprehensive overview of various definitions of modular products and modularity. He explains that there are various ways to describe the modularity of a product: by relations between the elements, by reasons and purposes, and in terms of product variety. Blackenfelt, however, does not provide a definition of his own, but he clearly illustrates the concept of modular products (Figure 3-2). The illustration is based on Simon’s idea of decomposability (1996). Thus, the strength and number of the relations within and between the modules defines the (modular) architecture.

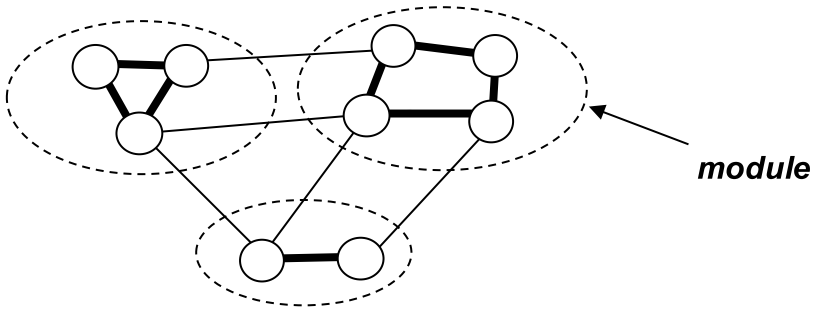


Figure 3-2 Modules identified by the relative strength of the intra-domain network relations (Blackenfelt 2001)

In the German design literature, the "modular system" is sometimes translated as "Baukastensystem" (e.g. Pahl et al. 2006). Koller (1998) defines "Baukastensystem" as a system, where the modules are mounted on a base part, but with freedom to place the modules in various positions.

Creating variety is one of the main purposes of modular products (Blackenfelt 2001). They fulfill various overall functions through the combination of distinct modules (Hillström 1994); modular products are easier to customize (Fagerström & Mats 2003). Baldwin & Clark (2000) propose modularity to manage complex systems by dividing the system into smaller pieces and considering each one separately. This separation allows the possibility not only to divide work tasks to ease the development, but to parallelize several tasks and thus reduce the overall time (Ulrich & Seering 1990). In this context Meyer et al. (1997) point out that modular product design has positive effects on production and manufacturing processes.

Origin and Example

The example below (see Figure 3-3) shows application of the modular design approach in the toy industry. The modularity helps to ease the change process. Single parts and modules can be redesigned instead of working on the whole product. Changes should usually affect only certain parts and modules of the product. Thus there is no chain reaction leading to a project restart. Modular products are often recommended when coping with changing environments. The less disturbed and hence accelerated development process of modular products over traditionally designed products has already been illustrated in Figure 1-1.

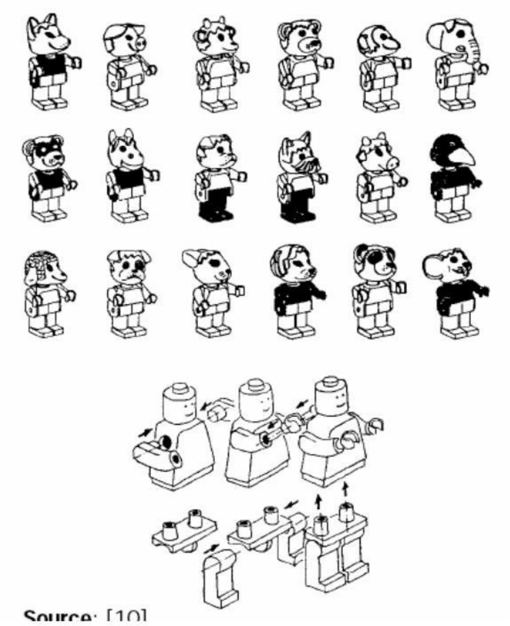


Figure 3-3 Example of modular design (Andreasen et al. 1988)

Modular product design is widely-used among several branches like aircraft (Woolsey 1994), automobiles (Nevins & Whimey 1994), consumer electronics (Sanderson 1994), household appliances (Sanchez & Sudharshan 1993), personal computers (Lariglois & Robertson 1992), software (von Hippel 1994), power tools (Sanchez & Mahoney 1996) and others (Möller et al. 2003). Hölttä-Otto states (2005) that modularization has become rather popular in academia in the last years even though it has been present in academia as well as in industry for several decades, especially in the automotive industry (Andreasen et al. 1988, O'Grady 1999).

Support

In order to support the development of modular products various methods and tools are proposed. They mainly aim at the fundamental problem of modularity, which is the partitioning of the design solution. Difficulties stem from choosing the most appropriate partitioning scheme given a multitude of constraints (Van Wie 2002). Hölttä & Salonen (2003) compares three different methods for optimal product modularization: 1. Function Structure Heuristics (Pahl & Beitz et al. 2007), 2. Modular Function Deployment (MFD; Erixon 1998) and 3. Design Structure Matrix (DSM; Ulrich & Eppinger 2004). All methods lead to different partitions of the products, as “some consider functionality and interface simplicity whereas others focus on strategic factors” (Hölttä & Salonen 2003). Therefore, Hölttä-Otto (2005) introduces a new six-step approach for the modularization process, which combines the advantages of the analyzed methods. It is shown in Figure 3-4.

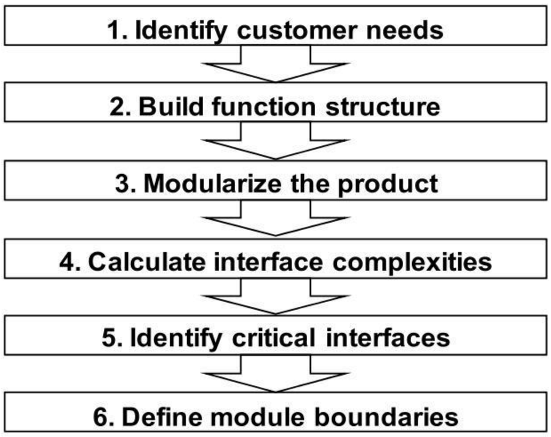


Figure 3-4 Modularization approach proposed by (Hölttä-Otto 2005)

Hashemian (2005) concludes that "most current modular design approaches aim to develop modules using component-based clustering. It is assumed that the interactions among various components can be quantified, and can be represented by graphs or matrices." Usually (conventional) methods of modularization can be used to achieve different benefits from the modularized design like simplified upgrading, versatility, variety, and customization. No matter which method is selected, "modularity has to be implemented in the early phases" (Marshall & Leaney 1999). Fricke & Schulz (2005) explain various types of modularity that have to be considered when developing modular products. They are illustrated in Figure 3-5.

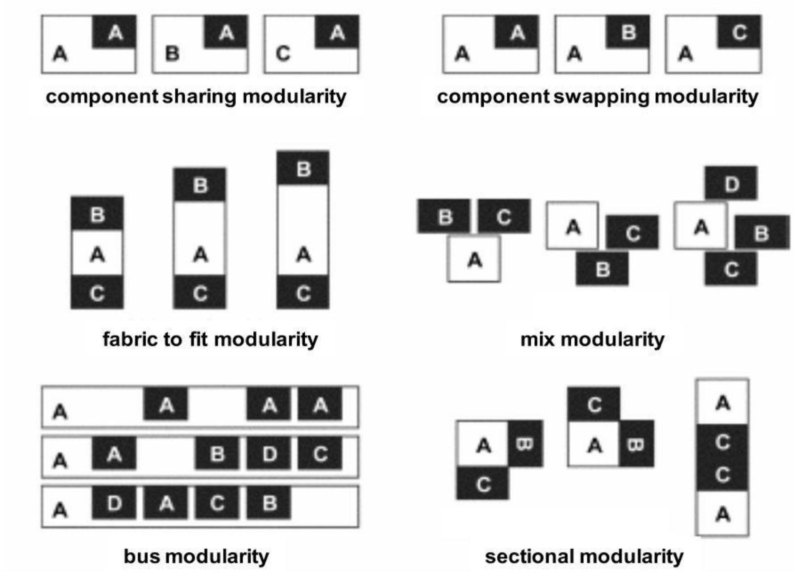


Figure 3-5 Various types of modularity (Fricke & Schulz 2005)

Dis-/Advantages

De Weck et al. (2003) state that modularity is a characteristic of a system that has higher adaptability and survivability under changing requirements. Various other advantages of modular designed products over integrated or traditionally designed can be found in literature. The advantages mentioned especially on modularity are:

- *Improved quality*
  as all resources for development and testing can be focused on the development of the modular product instead of being used for the development of various products at a time (Ishii & Yang 2003)
- *Shortened time-to-market*
  due to eased assembly (Ishii & Yang 2003), decoupled development tasks (and manufacturing, to some extent) (Stone 1997), eased concurrent design work (Smith 2007, Engel & Browning 2006), eased reuse of previous solutions and possibility of automation (Ishii & Yang 2003), simplified and accelerated product testing (Smith 2007)
- *Risk reduction and improved risk handling*
  due to integration of proven technology (module) (Ishii & Yang 2003), isolation of portions of the design subject to growth or high uncertainty (Smith 2007), protection of portions of the design where change would require heavy engineering, testing, or regulatory approval (Smith 2007), future emphasizing flexibility (Engel & Browning 2006) and eased functionality tests, but functionality of all modules does not guarantee whole functionality (Riepe 2003), great potential for limiting change and accommodating growth (Smith 2007)
- *Cost reduction*
  due to reduced development effort due to scale- and synergy effects, reduced differentiation (Riepe 2003), reused parts and module (Smith 2007), simplified supply chain, assembly and service (Ishii & Yang 2003).
- *Higher (overall) flexibility*
  due to improved device reconfigurability (Stone 1997), possibility of changing one part of the design without affecting other parts (Smith 2007), eased design reuse and incremental innovation (Smith 2007) and greater adjustability (Chakrabarti 2001) and thus higher product flexibility (Ishii & Yang 2003)
- *Eased development of variety*
  due to accelerated introduction for new derived products (Stone 1997), eased user configuration and mass customization (Smith 2007), eased design of size ranges, but more complex product development for the initial platform design (Riepe 2003), decreased cost for customer variation (Lehtonen et al. 2005)

- *Improved service*
  due to improved maintainability (Stone 1997) and product eased to service (Smith 2007, Riepe 2003, Lehtonen et al. 2005)
- *Optimized management*
  due to eased complexity management (Engel & Browning 2006, Smith 2007, Hölttä-Otto 2005), simplified organizational structures, for example, allow smaller design teams (Smith 2007), possibility of incorporating suppliers into design process (Smith 2007), life cycle orientation of the product (Lehtonen et al. 2005).

Besides offering several advantages modular design has its trade-offs. The most important ones, which have to be considered when applying the modular design approach, are listed below:

- *Reduced product performance*
  (Stone 1997, Ulrich & Tung 1991, Smith 2007), due to possibility of redundant structure and reduced function sharing (Ulrich 1995a), high number of wrong or incomplete configurations (Luhtala et al. 1994), increasing complexity of the product (Pulkkinen 2000), more weight and more space needed (Smith 2007), decaying of modularity over time (Smith 2007)
- *Higher initial costs*
  due to high effort for the development of the initial modular design (Stone 1997, Smith 2007)
- *Negative effects on business model, strategy, marketing etc.*
  due to similar look of devices eased imitation by competitors (Stone 1997), outdated and incomplete configuration model (Tiihonen et al. 1996), unforeseeable long-term consequences on business model (Smith 2007), more upfront planning necessary (Smith 2007).

Modularity is often considered as a fundamental necessity for flexible products operating in changing environments (Palani Rajan et al. 2003). However, it is more the loose coupling of the modules than the modularity itself that increases the products' flexibility (Orton & Weick 1990). It is clear that modular design, its benefits and trade-offs, the various methods and tools behind it should be taken into account when developing products in the context of uncertainty and a changing environment.

3.4 Flexible Design – Design for Flexibility

Definition and Purpose

Flexibility is a promising strategy for changing environments (see Chapter 2). Therefore, researchers and experienced product developers sometimes advocate the development of flexible products or the flexible development of products (e.g. Saleh et al. 2008). This approach was labeled as Design for Flexibility (DfF) by Palani Rajan et al. (2003). General definitions were given in Section 2.2.1, product related ones in Section 2.4.1, and a new one was proposed in Section 2.4.2:

> *Flexible products can be adapted to changes easily and reversibly – while easily is understood as economically and rapidly and reversibly as changeably back to what it was before.*

The idea behind developing flexible products can be on the one hand to offer a more flexible product to the customers in order to directly provide a product of higher value. On the other hand flexible products allow redesign, as a response to later changes, and design of new generations is easier to develop (Fricke 2006).

Origin and Examples

Several examples show that flexibility has significant beneficial effects for the company (e.g. Haberfellner & de Weck 2005). In Section 2.3.2 the positive effects are explained with examples from process and manufacturing flexibility. Design for Flexibility can often be found in the context of production processes. Flexible production in order to handle changing demands is vital in today's industry. For example, when Daimler-Chrysler introduced the PT Cruiser in 2000/2001 it was surprisingly successful. Demand quickly exceeded production capability in Mexico, where the PT Cruiser was built on the Chrysler Neon platform. Daimler-Chrysler was unable to deflect the production to Belvidere in the USA, because the production line (specifically the paint shop) could not be adjusted to the height of the PT Cruiser, which is a few inches higher than the Neon. Daimler-Chrysler lost approximately $ 480 million due to inflexibility (Haberfellner & de Weck 2005, Brown 2004). In contrast Audi AG invested in a flexible production system called "Drehscheibe", which allows the manufacture of different models in one production line. In this way volume variations can be balanced over different production sites (Audi 2007).

The international space station (ISS) was developed with late fixation of baselines. The delayed design freeze allowed higher flexibility and less change activities (NASA 1995). However, due to the international constellation of the program, the implementation of a single change still took on average 55 working days (depending on the kind of change) and thus changes were absolutely to avoid (Fricke 2006).

A simple example of product flexibility is given in Figure 3-6 below (repetition of Figure 2-20). The inflexible wooden chair (a) is not adjustable to the proportions of the person sitting at a table. It might be rejected due to incompatibility with either the user or the environment. The more flexible chair (b) can not only be adjusted to both, but readjusted several times later on, when the environment changes, e.g. for a different user or different table. The Design for Flexibility approach can be applied in order to achieve this kind of flexibility. However, the example also shows that product flexibility has its disadvantages as well. The more flexible office chair (b) is apparently more expensive to develop, more expensive to manufacture and despite its capability of handling changing environments, including a wide range of different users, maybe less robust in the classical mechanical understanding.

(a) **(b)**

Figure 3-6 Examples of inflexible (a) and flexible (b) products (based on Van Wie 2002)

Support

In order to achieve product flexibility the product development process can be supported by various tools and methods. Palani Rajan et al. (2005) proposed several design guidelines and a multiple-stage method, which can be applied during the design process. Chakrabarti (2001) proposes flexibility for products that require in-built ability to adjust settings, e.g. in control devices, to enhance the reuse of parts across product families, or to ensure minimal disruption to functioning in critical areas of the product. He gives general advice to the developer, like implementing modular design and making use of redundancies. Based on the aim of flexible designs Fricke (2006) uses the term Design for Changeability (DfC). He gives several principles to guide the product developer as well as to support company strategy on flexibility. Among these principles are:

- Clear design with precisely defined interfaces with low or no effect if one component has to be changed.
- Pro-active change management by anticipation of changes and application of risk management methods.
- Allowing late design freeze.
- Predefined change management including change process, configuration and version management.
- Flexible product development processes in order to handle changing aims and goals.

In contrast, the design guidelines of Palani Rajan et al. (2005) are more focused on the product itself instead of the development process. This way the guidelines are more specific. Exemplary guidelines are as follows:

- Modularizing the design leads to more product flexibility. As the design becomes more integrated, it becomes more inflexible for redesign.
- Designing the modules in a product as external attachments makes the design even more flexible.
- Designing with more standard components and interfaces will improve product flexibility.
- Directed partitioning of a design into a greater number of elements (manifested through higher numbers of components and functions) improves the flexibility.

Dis-/Advantages

Despite many advantages, the Design for Flexibility and Changeability approach has its disadvantages as well. Fricke & Schulz (2005) explain, when flexibility (they refer to changeability DfC) should be considered and when not. Based on Steiner (1998, 1999) they propose the flexible design approach, when the same architecture is used for different products and when the product has stable core functions, but variable secondary functions and/or external styling. Moreover, product flexibility is most beneficial, when the product has a long life cycle, and when the product is highly interconnected with its operational context. Product flexibility is also advised, when the product requires high deployment and maintenance costs. Reinhardt et al. (2001) propose flexibility for complex products and for highly unprecedented in an unknown market. Fricke & Schulz (2005) also propose flexible products for dynamic environments and strong competition.

In contrast flexible product design is considered as not cost efficient for all products, especially when the product is highly specific and when it is developed for ultrahigh performance markets with no performance loss allowed (Fricke & Schulz 2005). Moreover, flexible product design should be avoided for products with a short life cycle and for products, which are not built in great variety. Traditional product design is advised for products in well established and slowly changing markets or when the product is insensitive to change over time (Fricke & Schulz 2005).

There are various advantages related to the flexible design approach with its supporting methods and tools. These advantages refer to either the process or the product. For instance Rampersad (1996) lists among others the following advantages (also see Section 2.4):

- Strong decrease in the number of product parts.
- Faster time-to-market due to possibility of simultaneous assembly and testing of units.
- Simple and easily controllable assembly process.
- Easy accommodation of customer requirements and wishes; speedier reaction to market developments.
- Short product development time and a longer product life cycle.

These advantages have to be traded off against some of the disadvantages that usually come with product flexibility (see Section 2.4.6). According to Rampersad (1996) these are reduced performance, more weight, more required space, limitations of shape, over dimensioning, and additional costs for manufacture. Notwithstanding these trade-offs Design for Flexibility is often recommended for the development of products in uncertain and changing environments (e.g. Schulz & Fricke 1999, Saleh et al. 2008). Therefore, like the other approaches mentioned, Design for Flexibility, Design for Changeability and all related approaches, tools and methods are analyzed in order to derive a new set of guidelines as a support for the individual developer, as the actual support for developing products in changing environments is more on a generic level.

3.5 Platform Design

Definition and Purpose

A product platform can be defined as a "common set of parts" (Hashemian 2005). Similarly Robertson & Ulrich (1998) define platform as: "a collection of assets that are shared by a set of products." Otto & Wood (2001) give a definition, where a platform is a collection of common elements that are implemented across a range of products. They do not limit their definition to physical components. Meyer & Lehnerd (1997) provide a slightly more specific definition as they explain that components, modules and/or parts are shared so that "a stream of derivative products can be efficiently created and launched." Thereon Muffato & Roveda (2000) build up their definition: "a product platform is a set of subsystems and interfaces intentionally planned and developed to form a common structure from which a stream of derivative products can be efficiently developed and produced." Thus they already include the purpose of the platform strategy in the definition, namely to efficiently develop and provide a higher variety of products to better match the customers' requirements and expectations. Gonzalez-Zagusti et al. (2000) label the idea of sharing modules between several products so that communality used whenever possible as *modular platform approach*.

The different definitions of product platforms have been widely discussed (Lehtonen et al. 2005, Kristjansson et al. 2004, Jose & Tollenaere 2005, Hölttä-Otto 2005). Hölttä-Otto sums these up in the following definition, which is in line with scientific literature and industrial practice: "a platform is the common set of physical or non-physical modules from which multiple products can be derived."

Meyer & Utterback (1993) distinguish between product platforms and product families. The product platform consists of the structure and components shared by several products. Products, which share a common platform, but have specific features and functions required by different customers, are called a product family. "A robust platform is the heart of a successful product family, serving as the basis of a series of closely related products" (Erens 1996). New products can be derived as refinements or extensions of the platform. Figure 3-7 illustrated the relationship between modules, modular system, product platform and product family.

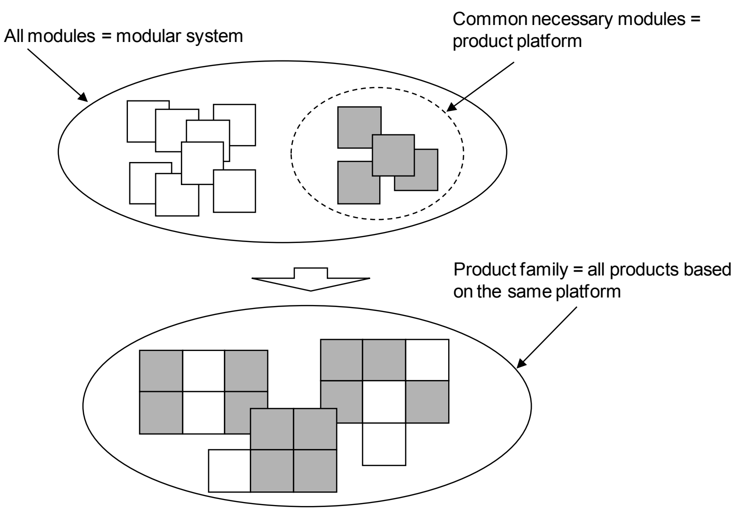


Figure 3-7 The relations between modules, modular system, product platform and product family (Blackenfelt 2001)

The fact, that product platforms share identical parts and modules, has notable effects on production and logistic processes (costs, investments, operations complexity, etc.); on development processes (development lead time, standardization, quality and reliability of design); on project organizational structure (teamwork, design task partitioning, relationships with suppliers); on knowledge (know-how transfer among projects, influence on and by technology, etc.) (Muffato & Roveda 2000). According to Simpson (2003) the main purposes are to increase variety, shorten lead times and reduce costs for product families; costs and effort for the development of the initial platform are usually higher than for a single product. Pahl & Beitz et al. (2007) add the aim of developing a great variety of products in short cycles.

Origin and Examples

Product platform design theory emerged from the mass customization paradigm of the late 1980s (Da Silveira et al. 2001) and was first known in the automotive industry (Pahl & Beitz et al. 2007). Volkswagen in particular has implemented the platform strategy successfully, but it is well known to all competitors (Rendell 2001). Other successful applications of platform design can be found in other branches like electric and electronic industry (Sanderson & Utzumeri 1995) and consumer goods (Jensen & Nilsson 2005).

Support

There are different ways to create product families based on product platforms (Simpson 2003): First, new and more modules can be added to the platform, removed and substituted. Thus, existing products are refined, and derivative products are generated, which are more likely to succeed than all new products (Association of National Advertisers 1984). The second way proposed by Simpson makes use of the size range approach as described in Section 3.7.

Dis-/Advantages

The advantages pointed out in scientific literature related to platform design are manifold:

- Increase variety (Simpson 2003).
- Shorten lead times (Hölttä-Otto & Magee 2006).
- Reduce costs (Stone 1997).
- Support company strategy (Lehtonen et al. 2005).
- Decrease costs for customer variation (Lehtonen et al. 2005).
- Support sales and product development and configuration (Lehtonen et al. 2005).
- Support production and maintenance (Lehtonen et al. 2005).
- Increase flexibility (Saleh et al. 2008).

Few disadvantages of platform design are mentioned: Platform design can be a risky strategy for companies as they depend largely on the quality and success of one or only a few platforms. Dependency on this single platform is much higher and can even lead to inflexibility when the whole product family has to be replaced. Development effort for the basis platform, from which derivates can be derived, is usually higher than for a traditionally designed product. Benefits usually occur for high production volumes. In fast changing environments this cannot be guaranteed and is much more difficult to achieve.

Saleh et al. (2008) point out, that platform design is “traditionally associated with flexibility (as an intuitive or self evident truth, although there is limited theoretical proof of this).” The platform based products can easily be modified through addition, substitution and/or exclusion (Simpson et al. 2001). Thus they provide flexibility to the product or the product family. Therefore platform design and its underlying design guidelines and tools should be taken into account when developing products to compete in uncertain and fast changing environments.

3.6 Architecture-oriented Approaches

Definition and Purpose

The architecture can be defined as “the manner in which the components (…) are organized and integrated” (Merriam-Webster 2006). Ulrich (1995a) is more precisely defining product architecture as: “(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specification of the interfaces among interacting physical component.” Smith (2007) provides the following definition: “Architecture is the way in which one assigns the functional elements of a product to its physical chunks and how these physical chunks interact to achieve the product’s overall function”. Maier & Rechtin (2000) extend their definition to the process as well: Architecture is “the structure (in terms of components, connections, and constraints) of a product, process, or element”.

Figure 3-8 after Harlou (2006) is based on his definition, which is formed as a consensus of an extensive literature study: “Architecture is a structural description of a product assortment, a product family or a product. The architecture is constituted by standard designs and/or design units. The architecture includes interfaces among units and interfaces with the surroundings.” In Figure 3-8 the terminology from Harlou is transferred, to the terminology, as it is used in this work; standard designs and units are understood as parts and modules; the surroundings are understood as the product’s environment.

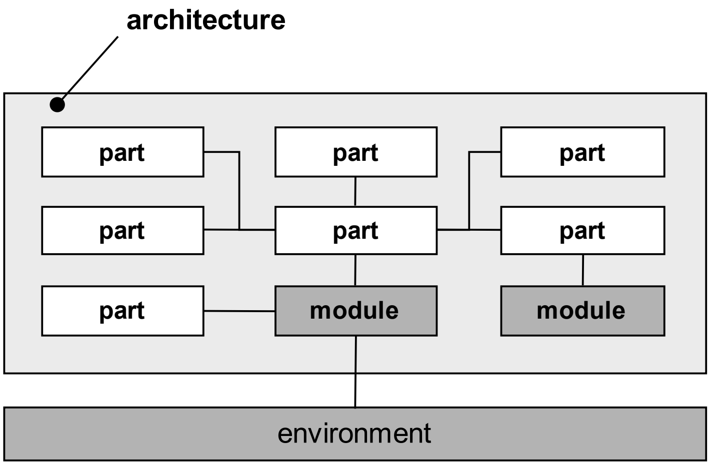


Figure 3-8 Product architecture (after Harlou 2006)

Example

Architecture design, also thought of more loosely as layout design within the context of conceptual design, is one stage of the design process that significantly impacts product performance in terms of manufacturing, assembly, modularity, product family variety, maintenance, etc. (Van Wie 2002). The example in Figure 3-9 illustrates how the same functionality of a product can be realized with different types of architecture in order to create a higher variety to the customer and to better match the specific requirements.

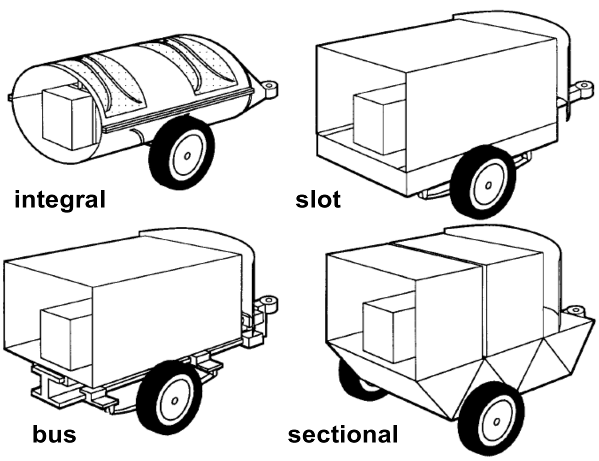


Figure 3-9 Four trailer architectures (Ulrich 1995a)

According to the definitions given above every product has its architecture. However, there are several approaches addressed specifically at product architecture for various purposes (e.g.

enhancing product flexibility, allowing product family extension, optimizing production). Product architecture is often considered as key factor for either products with a long life time, product families or modular and flexible products to perform in changing environments (Engel & Browning 2006). Therefore various tools, methods and methodologies have been proposed to support the development process and define useful architectures, module partitioning, and interfaces (Larses 2005).

Support

Larses (2005) points out that designing product architecture is often referred to as an art, which is performed in the conceptual stage of the design process. He proposes a combination of a key figure based methodology and the DSM cluster analysis, as this tool has shown successful application in automotive industry.

Van Wie et al. (2001) focus on the interfaces that a product's architecture implies. They propose guidelines for redesign to reduce assembly costs, as interface complexity and number are found to directly affect final costs. They offer a scheme to monitor the interface state of a product, which also makes use of DSM and Tree Representations.

Dis-/Advantages

Most of the architecture related approaches aim at a modular (and flexible) architecture to either easily develop derivative products or to prepare the product (family) for future (generational) enhancements. In this context, Mikkola & Gassmann (2003) compares products with modular architecture (also see Section 3.3) to products with integral design. Several benefits are highlighted. The modular product architecture benefits are (Mikkola & Gassmann 2003):

- Task specialization
- Platform flexibility
- Increase number of product variants
- Economies of scale in component communality
- Cost savings in inventory and logistics
- Lower life cycle costs through easy maintenance
- Shorter product life cycles thorough incremental improvements such as upgrade, add-ons and adaptations
- Flexibility in component reuse
- Independent product development
- Outsourcing
- System reliability due to high production volume and experience curve.

Product architecture can be integral. This is usually not proposed for products dealing with uncertainty and/or fast changing environments. However, the integral design provides several benefits as well that have to be taken into account when developing the product architecture. According to Mikkola & Gassmann (2003) the benefits of the integral designs are:

- Interactive learning
- High levels of performance through proprietary technologies
- Systemic innovations
- Superior access to information
- Protection of innovation from imitation
- High entry barriers for component suppliers
- Craftsmanship.

When assessing the product architecture it has to be clear that in general the benefits of modular design are the down sides of the integral design and vice versa. Thus, defining the optimal architecture is challenging. Like the quality of the whole product, it is difficult to evaluate the quality of the product's architecture, especially during the development process. According to Rechtin & Maier (1997) the quality of architecture can be measured retrospectively by its lifetime: the longer the lifetime the better the architecture, but this is of little use for developers.

3.7 Size Ranges and Design for Variety

Definition and Purpose

Ulrich (1995b) defines product variety as the diversity of products that a production system provides to the marketplace. Focusing on the production and manufacturing processes, he highlights the importance of variety for manufacturing competitiveness. This variety is often achieved by the development of size ranges.

A size range consists of technical artifacts (machine, module, part), which fulfill the same function with the same solution principle in different size steps and with preferably the same production method and material (Pahl & Beitz et al. 2007).

Figure 3-10 shows a gear box size range. All gearboxes make use of the same solution principle and (presumably) the same production technology. They come in eleven different size steps and thus form one size range.

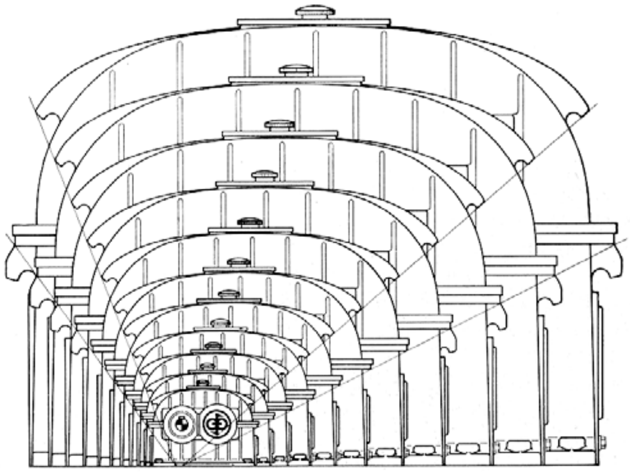


Figure 3-10 Display of a gearbox size range (Pahl & Beitz et al. 2007)

Size ranges are not to be mixed up with product families. Product families are defined as “a larger set of end products constructed from a much smaller set of components” (Ulrich & Tung 1991). Martin & Ishii (2002) point out that there are two types of product variety. The first is within the current product line and the second is the variety across the future generation of the product. They define the variety in the current product line as spatial variety resulting in product families and the second one across generations as generational variety resulting in product generations. These two concepts of variety are illustrated in Figure 3-11.

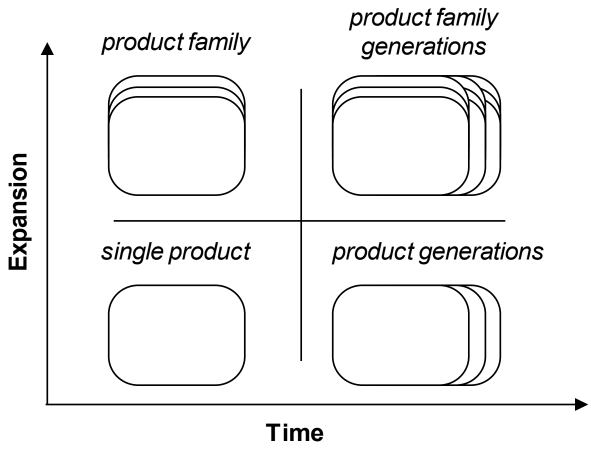


Figure 3-11 Spatial and generational variety of products (based on Hölttä-Otto 2005)

Figure 3-12 below illustrates the different concepts behind size ranges in comparison to modular products (see Section 3.3). While modular products provide a variety to the customer by arranging identical modules in different ways, the size range products make use of different modules (different sizes), but identical module arrangement and same solution principles.

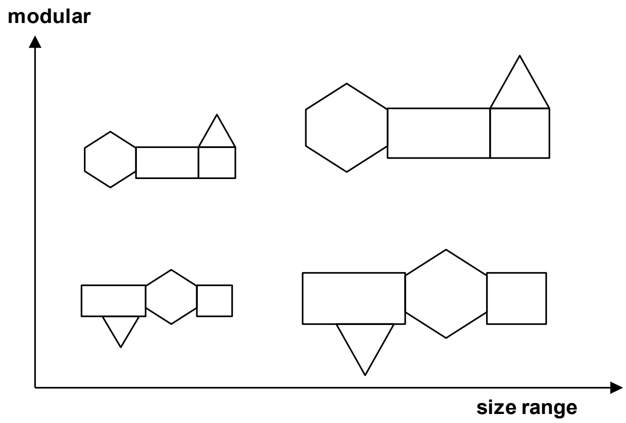


Figure 3-12 Modular dimension and size range dimension for the generation of variant products (Blackenfelt 2001)

The basic idea of developing size ranges is to define one standard design and reuse it, its documentation and, if possible, its production processes (Harlou 2006). This reduces the development effort. Fricke & Schulz (2005) recommend offering a higher variety of products (product sizes) in order to handle the increasingly specific demands of the customers.

Origin and Examples

Developing size ranges and thus offering the customers a variety of products to choose from is applied not only for standard machine elements, but in many branches and products like automated teller machines (ATM), aircraft, aircraft engines, automobiles, consumer electronics, microprocessors, personal computer, power tools, etc. (Sundgren 1999). Often size ranges are used in combination with platform (see Section 3.5) and/or modular design (see Section 3.3) approaches.

Support

Martin (1999) provides a method (Design for Variety - DfV) that can easily be applied to develop a great variety of products. His method is not limited to size ranges, but makes use of other approaches like platform and modular design as well. Pulkkinen & Bongulielmi (2004) mention four ways of creating product variety: varying the type of an element, the number of similar elements, the attribute of an element and/or the (topological) relations of elements. They highlight the development of size ranges as a good approach for varying the type of an element.

A simple six step method to support the development of size ranges is introduced by Pahl & Beitz et al. (2007):

- Define primary layout for new product or existing product
- Define physical dependencies (exponents) with help of similarity laws
- Define size steps
- Adaptation of theoretical size ranges to standards and technological boundaries
- Embodiment design of modules and critical zones
- Optimize and complete data, including production documents.

Dis-/Advantages

Developing size ranges can help to save costs (Fujita 2000). These cost savings are realized by reducing research and development costs (development effort only once) and lower production costs (higher volume), moreover, production and development can benefit from learning effects. Thus it is more likely to achieve higher quality. The delivery time is shortened and spare and replacement part supply is eased (Pahl & Beitz et al. 2007). On the downside of size ranges is the limited choice of size. The provided products usually do not perfectly match customer requirements unless a size range is developed with very small steps. The customers have to compromise on functionality or select a product from a competitor.

Size ranges and product variety can support the development of products for uncertain and changing environments, even though size ranges are not necessarily flexible or robust. Products from size ranges can be used in addition to other approaches like platform or modular design. Moreover by offering a range of products it is more likely that at least one of the products matches the new requirements that emerge from the changed environment.

3.8 Mass Customization

Definition and Purpose

Mass customization is an oxymoron. It is putting together the seemingly contradictory notions of mass production and individual customization (Pine 1999). Mass production with its highly efficient processes helps to reduce costs, while customization of products is applied in order “to make or change something according to the buyer's or user's needs” (Cambridge Dictionary 2007) and thus provide higher value. Mass customization aims at combining both of these benefits in one product. It is applied by the industry as a response to rising consumer expectations (Hashemian 2005). In order to implement the mass customization strategy companies make use of platform design, Design for Variety and product family design, while there is especially a strong link between platform design and mass customization (Martin & Ishii 2002). Pine (1993) strongly promotes the strategy of mass customization. According to him, it is a useful concept for providing "variety and individual customization, at prices comparable to standard goods and services (…) that nearly everyone finds exactly what they want." Tseng & Jiao (2001) provide a pragmatic but precise definition for mass customization. Mass customization corresponds to "the technologies and systems to deliver goods and services that meet individual customers' needs with near mass production efficiency." According to Piller (2004, 2006) the term mass customization is "used for all kind of strategies connected with variety, personalization, and flexible production."

Eckert et al. (2003) analyzed the relation between changes in the development process and mass customization. They conclude that changes occur throughout all stages of a design life cycle. Changes in the later phases of the development processes are well handled with the mass customization approach.

Examples

There is a trend for individualization (Ruf 1998). E.g. in the automotive industry it is possible, that from all possible variants less than one car per variant is build. Successful examples of mass customization can be found in various products like cars, bicycles, houses or insurances (Da Silveira et al. 2001). However, Piller (2004) complains that even though the opportunities of mass customization are acknowledged as fundamentally positive by theoretical and empirical studies for many years, the application is way behind its potential. In general, only small start-up firms "utilize [the] novelty effect of mass customization to enter mature markets. Large scale mass customization operations are still limited to a few examples" (Piller 2004). Piller highlights the following reasons for this:

- Terminological problems
- A shortage of reliable information about the real demand for customized products in various markets
- The state of implementation of configuration technologies
- Lack of management knowledge about organizational and strategic capabilities of mass customization operations.

Support

Despite the mentioned problems there is support for developing mass customized products: Krishnapillai & Zeid (2006) propose a mathematically based method in order to find the optimal product design specifications. Tiihonen et al. (2003) describe a configurator prototype that supports the configuration of mass customized products. Da Silveira et al. (2001) propose to combine quality function deployment (QFD) (Cohen 1995) with the importance performance matrix (IPM) of Slack

(1994). First, customizable features in products (and services) can be identified and ranked. Then IPM is used in measuring the ability to deliver the required level of customization.

The support provided by literature on mass customization (e.g. Pine 1999, Piller 2006) is often more focused on the business, organizational and managerial issues of the mass customization strategy. Explicit advices for product design are secondary. They refer to other development strategies like platform design (see Section 3.5), architecture focused approaches (see Section 3.6) and others.

Dis-/Advantages

Mass customization has several advantages. Most important is that a great variety of customers can be provided with highly individual products that should almost perfectly match their requirements. These products can be manufactured at (almost) mass production costs. Thus high value products can be offered at competitive prices. On the downside of mass customization are more complex and new business strategies that have to be implemented carefully. Logistics is more challenging than on single product mass production. The whole supply chain can become more complex. The customizing process can either encourage or deter customers to purchase the product, as it can be understood as higher value due to participating in the development as well as additional effort for the customer, when purchasing the product. Assessing the right degree of customizability and type of customization is a crucial task for the developers. Moreover, by using further approaches like Design for Modularization (see Section 3.3) the trade-offs of these approaches on the products are triggered down to mass customized products as well.

Mass customization and all its underlying methods, methodologies and strategies can support the development of products for uncertainty and changing environments, even though (mass) customized products are not necessarily flexible or robust. By offering an (unlimited) variety of products, it is more likely that at least one of them matches new requirements that emerge from the changed environment. Hence the benefit of mass customization in changing environments are on the company side, as redesign and change effort is reduced; the customers do not directly benefit from this kind of flexibility, as their products can be affected by changes in the environment.

3.9 Miscellaneous Approaches & Concepts

Besides the approaches described above there are various additional approaches for product development, which can help to handle changes in the environment by a specific product design. These approaches are less elaborate and well-established in both academia and industry. Here they are briefly described as these and the underlying ideas, tools or methods might be helpful for developing products for changing environments. Useful fragments are integrated in the newly derived set of guidelines (see Chapter 4).

Design for Adaptability

Various researchers describe the Design for Adaptability (or Design for Adaption) approach. Depending on the background and research area of the person, the approaches are focused on different aspects and are proposed for different contexts.

Engel & Browning (2006) define adaptability as "the ability of the system design to be changed to fit altered circumstances, where circumstances include both the context of a system's use and its stakeholders' desires." Upgrades and variants aim to increase the value and profitable life of the product by closing emerging gaps between requirements and capabilities. Upgrading and creating variants is easier when a system has been designed to facilitate and accommodate such changes (Engel & Browning 2006). Thus, Hashemian (2005) proposes adaptability in order to create variety and versatility. According to him versatility is just a special form of adaptation. Adaptability is a characteristic (Gu 2002; a property in the definition of Weber (2007)) of the product that can be designed into it. According to Gu (2002) higher adaptability can in general be achieved by upgrading, (mass) customization, new models, and extended service life. Hashemian (2005) proposes a method and guidelines to support the development of adaptable products. The benefits for either design adaptability for the company or product adaptability can be clustered for the user, producer and the environment (Hashemian 2005).

The user's benefits are a larger variety to choose from at lower costs, product familiarity, possibility of upgrading and customization, and adaption to the changing needs of the user. The producers mainly benefit from lower costs and time for design and production, quick market response and technology update, higher market share due to variety and mass customization, and better market acceptance. The benefits for the environment are listed as a better use of resources during production, parts salvaged due to shared modules, more service with fewer products, and less waste and pollution.

Besides classical mechanical engineering application, Design for Adaptability can also be found in housing and infrastructural business: Habraken (1980) describes adaptable housing projects in Cairo. Specifically built houses with adaptable layout aim at handling the changing requirements of the inhabitants that can occur e.g. due to family expansion. Intensive user integration additionally helps to match the time-variant demands and wishes.

Similarly the City of Vancouver proposed Adaptable Design Guideline for housing projects (Hashemian 2005). The adaptable design is used to create livable residences for a wider range of persons. "Through consideration of how adaptations could be easily and inexpensively incorporated at a future time, Adaptable Design will allow for changes which are required by residents with varying or changing needs, thereby supporting independent living (for those with moderate disabilities)…. new developments and technology may result in equivalents that meet the intent of a specified requirement" (Hashemian 2005).

Adaptronics

A specific form of adaptable design is described by Hanselka et al. (2001). Adaptronics are actively self-adapting products, parts or structures. They react to external changes. Usually this requires an electric or electronic feedback loop to adjust the dimension of adaptation. The term adaptronic is a combination of adaptive (structure) and electronics (Pahl & Beitz et al. 2007). According to Hanselka et al. (2001) adaptronics are an integration of mechanical engineering structures with the possibilities offered by electrical and electronic technology supported by control and information technology. Figure 3-13 below illustrates how adaptronics can be combined with classical mechanical components in order to improve the properties of the product.

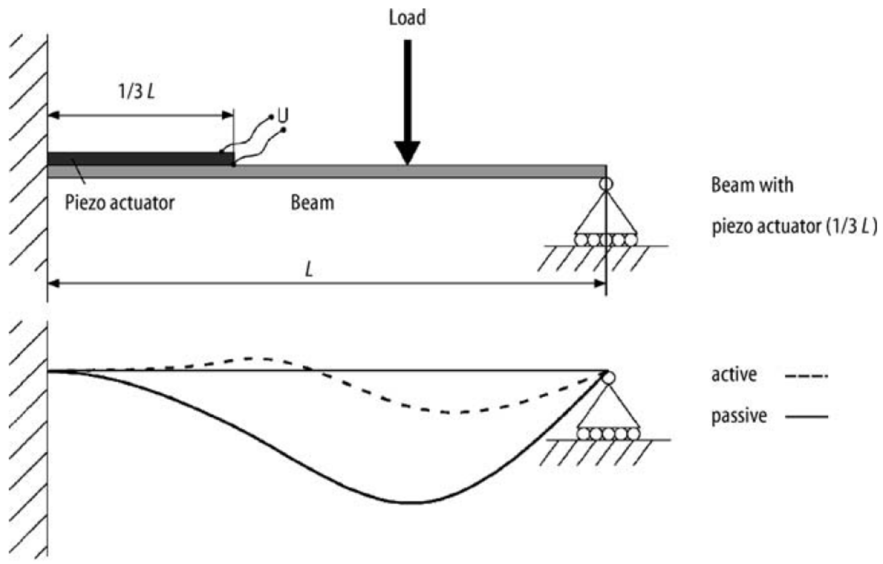


Figure 3-13 Adaptronic application in non-deforming beams (Hanselka et al. 2001)

Adaptronics can help to handle the changing environments of the product in the same way as (classical) adaptable products. Thus they are considered useful for the new approach described in Chapter 4.

Design for Appropriation and Design for Serendipity

Design for Appropriation and Design for Serendipity aim at an enhanced flexibility for the user. Moran (2002) states that "the users adapt the products their way", which is not always the same way the designer intended. It can be interpreted as an unintended flexibility of use. This kind of flexibility is not within the scope of this work (see Section 1). However, even this adaption of products by the user to change existing situations into preferred ones, can be understood as design activity (Simon 1969). Dix (2008) suggests different design guidelines for the product designer in order to ease the later adaptation activity for the users. These design guidelines (e.g. "allow interpretation") are also considered in Chapter 4 for the new set of design guidelines.

Design for Agility

Agility is often used synonymously for flexibility. While flexibility is preferably chosen in product development, agility is more often related to software development (Smith 2007). However, Haberfelner & de Weck (2005) describe agility as a specific way of thinking in systems engineering or product development. In their opinion agility is a combination of flexibility and speed in the whole process, including planning, designing and manufacturing. The agile product development process is "nimble, dexterous and swift" (Haberfelner & de Weck 2005). It is adaptive and responsive to new and unexpected information during the process. It can be described as the opposite of the traditional development process, where requirements and design solutions are frozen as early as possible (Haberfelner & de Weck 2005).

Agile software development (e.g. Martin 2002) often refers to the Manifesto for Agile Software Development (Beck et al. 2001). The Manifesto consists of twelve principles, which are believed to improve development by making it more agile, effective and leading to better products. These design principles (e.g. "Welcome changing requirements, even late in development…") are also considered in Chapter 4 for the new set of design guidelines to support the development of material products.

Design for Agility has similar trade-offs as Design for Flexibility (see Sections 2.4.6 and 3.4). It requires more thinking, planning and rethinking than the traditional development approach (Haberfelner & de Weck 2005).

Design for Dis-/Assembly

When changes occur after the material product is manufactured it either has to be completely new or redesigned and newly manufactured or it has be disassembled, partly reworked, and later reassembled. If the Design for Assembly (DfA) approach is applied to the product the implementation of changes into the manufactured product is eased. Thus, the Design for Dis-/Assembly is taken into consideration for developing products for changing environments.

Design for Assembly is derived from automated and robotic assembly (Rampersad 1996). Various methods exist to optimize the product design, and thus reduce the complexity of the assembly process in order to reduce costs. These methods are based on empirical information about assembly operations and on the knowledge of experienced designers. This experience is collected and made accessible to the public (e.g. Boothroyd & Dewhurst 1983). A simple yet effective way to spread this knowledge is with the help of design guidelines. One example is shown in Figure 3-14. With the help of guidelines like these the product developer can improve the assemblability of the product.

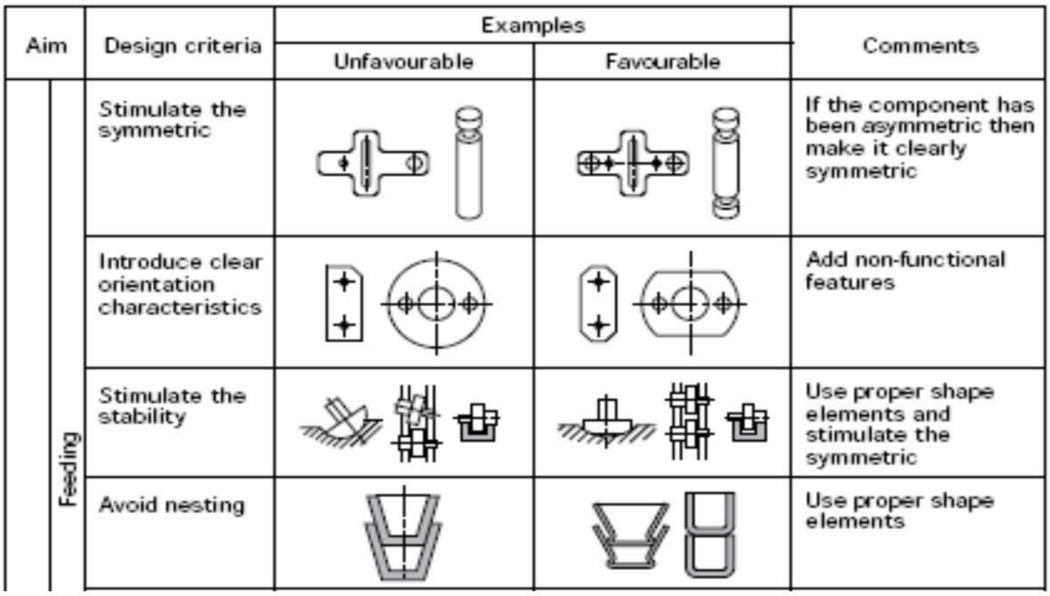


Figure 3-14 Design for Assembly (Pahl & Beitz et al. 2007)

Originally, Design for Assembly is limited to the assembly process itself. In this work the DfA approach is taken into account for the new flexibility guidelines as well, as the eased dis-/assembly of the product enhances the product's flexibility. Benefits due to this flexible design might be beneficial even during the development process.

Multi-Life Products

Pahl & Beitz et al. (2007) introduce the Multi-Life Products. These products are designed in a way, "that, for instance, later function variants and additions can be realized without redesigning the product" (Pahl & Beitz et al. 2007). As for flexible and robust products, (see Section 2.4.2) possible future requirements have to be taken into account when planning and designing the actual product. Even though these requirements are not implemented in the first product launch, the products can easily be adapted later on. Pahl & Beitz et al. (2007) propose several design principals and guidelines for the development of multi life products. These, are for example, standardizing mechanical, electrical and software components, and clearly defining (standardized) interfaces between the different parts of the product. Thus the multi life product approach hardly differs from Design for Flexibility or Design for Adaptation. Compared to these approaches, multi-life products primary deal with expected future changes, while flexible and robust products are designed to handle unexpected changes and provide larger variety.

Living Products

There is a group of product development approaches, which specifically take into account the changes that occur during the use phase of the product life cycle. They mainly focus on providing a high value to the stakeholder throughout the product's life by fulfilling new and changed requirements in later use phases (Engel & Browning 2006). Thus, the product's value does not diminish over time.

Blessing & Schmidt-Kretschmer (2004) highlight several issues influencing the modern product development like the conflict between sustainability and product life cycle, increased ecological awareness of company and user, higher demand on sustainable products, shortened development time and use phase. They state that in the use phase of the product a mismatch between the users' requirements and the product properties occur due to cumulatively changing requirements. According to Blessing & Schmidt-Kretschmer (2004) traditionally designed products with extended life time barely solve this problem. Neither is acceptance of an early end of product life a satisfactory solution. Thus, they postulate a new, sustainable solution to break the described trend: Products have to be developed in a way that they can easily be adapted during use phase. By reconfiguring (or redesigning) the product it gets a new "life", so that the overall product life time can be greatly extended, and the product value (to the customer) remains high. Instead of developing static products that only fit to temporary requirements for a short period of time, products have to become more "dynamic" and "living".

This approach is similar to others mentioned before. However, the idea of living products is yet to be researched intensively. New methods and tools (e.g. from other business and scientific disciplines) have to be developed to support the designing of living products. For now, there is only the reasonable vision of products that can be adapted to changing wishes, demands and environments of the user. This can be beneficial either in everyday or business application. New and existing technologies can be combined as well as products and services in order to optimize the living product. As the word living indicates, the product is understood as much more than just a technical artifact. Ideally it becomes a kind of comrade to the user. This way a high customer loyalty to the product can be achieved.

3.10 Summary and Discussion

In Sections 3.1 to 3.9 various approaches are introduced that can help to design products for changing environments. The approaches have been chosen, because in one way or another they support the development of either flexible or robust products or include other ideas that for instance ease the changing and adapting process.

Figure 3-15 illustrates the application of the different approaches to one example. A table leg has to match a specific length. In order to achieve the optimal length the optimized product design makes use of various input parameters and calculations. The robust design approach aims at providing a design solution, which does not need to be changed, even when the initial requirements (length) change over time. In the example one table provides different heights. If for instance the users of the table grow, they can change from the lower to the higher side of the table. The table itself does not have to be adjusted. The modular design approach makes use of various different modules (for the table leg). The modules can be combined (and be exchanged in future) to the specific requirements of the customers. The flexible design approach provides a solution, where the product is flexible and hence can be easily adapted to new requirements (a new length). The example of platform design illustrates how one specific product (one specific table) can be built on an initial platform. It is not shown in the figure that this platform can be used for a range of different tables. The example of the architecture approach does not show a specific table or table leg, but how various parts have to be arranged in order to form a useful architecture for the table. The size range approach offers a set of different table legs and the customers can choose, which one matches their requirements best. In contrast, when applying the mass customization approach, the table leg can be specifically made (cut, respectively) to match the customers' requirements. The Design for Appropriation approach is chosen to illustrate one example of the miscellaneous approaches in Figure 3-15. Beer coasters are used in order to adjust the length of the table leg to its required length, despite the fact that they have been designed for a completely different purpose.

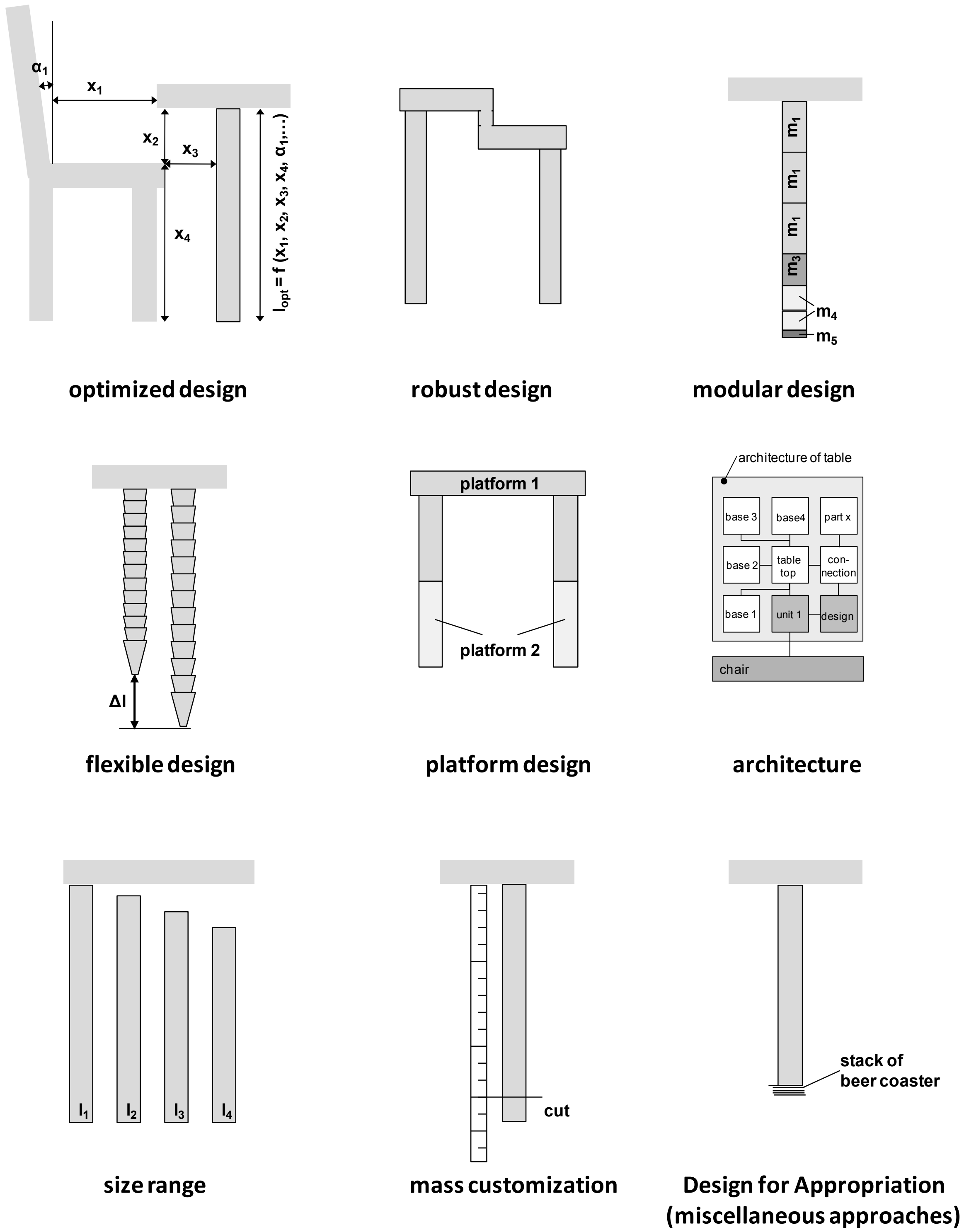


Figure 3-15 Illustrating the approaches described above for one example of a table leg, which is required in a specific length

In order to sum up why the approaches, which are described in this chapter, form the basis for a new support, an overview of the different approaches is given in Table 3-1. The goal and aim, the basic idea behind the approach and the relation to the approach of Developing products for changing environments, i.e. Design for Flexibility (DfF), are highlighted.

Table 3-1 Overview DfX approaches

Aim	Basic Idea	Why useful for Design for Flexibility (DfF)
optimized product		
match customer requirements with a single product (one-of-a-kind)	specifically develop the product for a temporary fixed set of requirements	developing optimized products is about matching customer requirements - even though these are considered fixed, useful ideas for flexible and robust products, where requirements change over time, might be derived
robust product		
match customer requirements with a single product even when requirements change over time	design products that will fulfill the requirements without product change, even if the requirements changes	developing robust products is about anticipating changes and making product changes obsolete by integrating possible future requirements, which are caused by changes in the product environment
product modularization		
the aims of product modularization are diverse: e.g. matching customer requirements with a single product or with multiple products	different ideas are behind product modularization: from creating product variety to enhancing the flexibility for the customer	product modularization (and lose coupling between the modules) is one of the basic principles behind DfF and thus has to be taken into well consideration/analysis for the new DfF approach
product flexibilisation		
the aims of product flexibilisation are diverse: e.g. enhance product flexibility for the customer (= higher value), match different requirements with a single product	enhance the product flexibility for the customer and also adjust the product to diverse and changing requirements	the approaches analyzed for product flexibilisation (including Design for Changeability) aim directly at enhancing the product flexibility and are thus useful for the new DfF approach
platform based approaches		
offer a variety of products for the customer by using a common platform	create a variety of products in order to match the different customer requirements while keeping the costs low by using platforms and similar parts	platform based product design is often intended to enhance flexibility of a product or product basis in order to easily create a variety
architecture oriented approaches		
match customer requirements with a single product	adjust the product to the requirements by focusing on the arrangement of the functional elements and their interfaces (architecture)	architecture is not only elementary for the functionality of a product, but also for the flexibility
size ranges, product family and variety		
match customer requirements by offering multiple products	offer a great variety to customers and let them choose the one product, that fulfills their requirements best	developing size ranges and product families often makes use of methods, principles and tools that may also be used to enhance product flexibility
mass customization		
match customer requirements with individual products based on mass production	combine mass production and customized products in order to match the individual customer requirements	mass customization enhances the flexibility to serve different customers and environments
miscellaneous approaches		
the different approaches clustered under miscellaneous approaches have diverse aims.	enhance the product flexibility for the customers and/or adjust the product to their requirements	e.g. Design for Assembly eases the (dis-) assembly process, which is necessary when changes have to be implemented in the material product. Thus the change procedure is simplified, which supports the DfF idea

Application and Support

The application of the various approaches described in this chapter and the support they provided varies widely. Scientific literature, derived from industrial application as well as purely academic, describes identical approaches often from a different point of view. In Table A1 - 1 in the appendix[7] (excerpt in Table 3-2) an overview of the different literature is given. The literature is grouped according to approach and compared based on:

- *Main benefit*, the main beneficiary for this approach: customer or company
- *Main goal*, the goal to be achieved by applying approach
- *Basic idea*, how it works
- *Background*, from where the approach is derived (or background of research)
- *Support*, what kind of support is given to the product developer
- *Possible use and application*, in what phase of the process or at what part of the company the approach can be applied
- *Target domain*, where the benefits of application of the approach are derived, either production or development or other.

Table 3-2 Application and Support – literature overview (excerpt of Table A1 - 1)

Approach	Main Benefit		Main Goal					Basic Idea					Background						Support								possible Use/Application						Target area / Domain		
	company	customer	create flexibility for customer	match customers' requirements with diverse products	match customer requirements with single product	reduce costs/time	other	optimise production/manufacturing	enhance product flexibility	create variety/range of products	adjust product to requirements	other	accademic (not applied)	aerospace	automotive	consumer goods	software and IT	other	awareness	understaning	strategy	method/methodology	calculation (-tool)	computer based tool	guidelines	other	strategy (company)	product portfolio	product planning	conceptual design	embodiment design	other	production/manufacturing	development	other
product modularisation																																			
Andersson & Sellgren 2002	●						○				○	○	●									○		○					○	○				●	
Baldwin & Clark 1997	●			●		○			○	○	○		●						○	●	○						○		○						○
Blackenfelt 2001	●			○	○	○					○	○							○			●			○				●	●				●	
Cebon et al. 2002	●				●				○		○		●						○	○	○	○	○	○					○					○	○
Erixon 1998	●			○	○	○	○		○	○	○		●									●			○				●	●				●	
Hölttä & Otto 2005	●				○	○	○		○		○	○	●					○				●							●	●				●	

Most descriptions highlight the benefits for the company. This is possibly due to the fact that especially those approaches have been taken into consideration that presumably support the handling of change that occur before the product is fielded. Even though not mentioned specifically in every reference, the underlying goal of most of the introduced approaches is to optimize the product to match the customers' requirements, respectively to reduce the mismatch that often occurs

[7] All Tables indicated with A, such as Table A1-1, can be found in the appendix.

during product use. The better matching of requirements is often accomplished by offering a greater variety (basic idea). This can for instance be achieved by the development of size ranges, by mass customization or by making use of the platform strategy. The basic idea behind other approaches is less clearly defined. Especially for the Design for Flexibility related approaches, the idea as well as the main goal is often not communicated directly and is therefore unclear. As the analyzed references are all scientific papers and books, the background highlighted in the table is mainly scientific. However, various references are based on industrial case studies or have been formulated by industrial practitioners. The support for the approaches described in the references widely varies from creating awareness for a phenomenon to specific computer based tools directly supporting the design process. With the highly scientific background, many of the references aim at creating awareness for a phenomenon and enhance the understanding. Instead of supporting the product developers directly, the developers' knowledge related to one of the approaches is widened so that application for the developer during the process is easier.

All of the approaches can and should be considered at all levels of a company: from strategic planning, portfolio management, specific product planning, conceptual and embodiment design. Most of the references see the main benefits of the application in the development department. Some refer to positive effects for production or other not specified areas.

Limitations

Even though positive results in industrial application from the various approaches can be found, there is considerable room for improvement. Most descriptions of the approaches are abstract and vague, goals and ideas barely defined and support is basic– especially in the design phase.

The different approaches are related to the same context and sometimes aim at the same goal; nevertheless the ideas behind them are different. The support provided differs widely from creating a general awareness of a phenomenon to precisely defined methods for the individual developer. This and the partly contradictory goals make it difficult to apply more approaches at the same time in order to combine all their benefits. Trade-offs are mentioned, but how the developer has to cope with contradictive aims and goals from other approaches that are not mentioned in this work (e.g. Design for Light Weight) cannot be clarified on a general level. Without further instructions the developer has to work on his own, not supported by methods, tools, guidelines, etc. General, yet precise descriptions, which can support developers with their every day routine, are hardly to be found.

Often the support provided through the references is focused on generic level, thus support to the individual developer is limited. It often aims at creating awareness, enhancing understanding and supporting the strategic planning of the company. According to the model of design activities by Fricke (1996, Figure 3-16) the support is allocated to the more abstract levels. The design action and design routine are least supported.

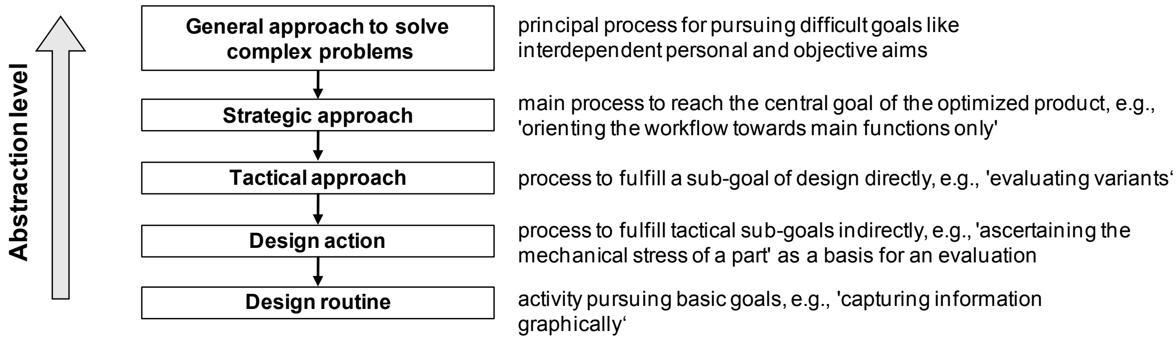


Figure 3-16 Model of Design Activity levels (Fricke 1996)

A further limitation of the approaches as they are described is their retrospective character. They are often derived from successful product development projects and it is taken for granted that they will provide similar positive results in future projects. Their universal validity is yet to be proven.

Conclusions

The diversity of the approaches, their support and application make multiple applications in one development project challenging. Support is not consistent among the approaches, though the underlying aims are the same. Not all support is accessible to everybody, as it was partly developed for company internal use. Acquisition and implementation is often time consuming and challenging. Even when implemented correctly, not all existing tools deliver useful, efficient and user-friendly support (e.g. Vajna et al. 2007).

After all, some of the analyzed product development approaches (see Chapter 3) are supported with design guidelines (e.g. Palani Rajan et al. 2003). These guidelines are easy to understand and apply. The actually known number of guidelines for the development of flexible products is, however, limited. Thus, Saleh et al. (2008) raise the question “what other design guidelines and architectures provide flexibility?”

This question is answered in the following chapter, where based on the promising ideas and approaches described above new guidelines for the development of flexible and robust products are derived.

4 GUIDELINES FOR DEVELOPING FLEXIBLE PRODUCTS

In Chapter 3 various promising approaches to support the development of products for changing environments have been described. Good ideas are implemented already and deliver good support. However, most of the approaches are focusing on specific aspects only, they are not comprehensive. They are neither consistent nor standardized. Some are difficult to understand and implementation and application is challenging as well. Often the situation is analyzed, but the transformation of the findings to engineering design practice as proposed by Ali Khan & Wallace (2003) is insufficient.

In the following sections of this chapter, a new set of guidelines is introduced. It aims at supporting the development of products for changing environments. By offering these guidelines the actual situation, especially the lack of simple, yet comprehensive support shall be improved.

4.1 Intended Support

Support for developing products is needed, especially when requirements are likely to change or are presently unknown. The product development process in general is well defined and supported (e.g. Pahl & Beitz et al. 2007). The various different ideas behind design support, the various different approaches and the various differing descriptions of the same approach make the situation fuzzy. If support is needed, it is challenging to find the right tool. The choice is wide: design guidelines, computer based tools, CAD and CAx-systems, calculation models, catalogues, methods and methodologies are offered to support the development products for changing environments.

The product development process is rather complex (Gries & Blessing 2006). Effort is put into it in order to accelerate and thus reduce time-to-market (Maier & Rechtin 2000). The support presented in the following aims at supporting this situation for the people taking part in the process, especially the individual product developer. The whole development process can be accelerated (mainly by reducing and easing iterations) and thus shortened. Moreover, the final results can be optimized for the competitive market situation. This shall mainly be achieved by giving the product developer help in uncertain situations during the process. Higher contentment and motivation of the people involved should lead to better and faster results (Pahl & Beitz et al. 2007).

The support has to be efficient, i.e., possible benefits that can be derived from the support (e.g. time savings) have to be well balanced to costs and effort for implementation. Complex computer based design process support systems can be troublesome (e.g. Vajna et al. 2007). Tools should be simple and easy to understand and user friendly (Jänsch et al. 2003). “If you can’t explain it in five minutes, either you don’t understand it or it doesn’t work” (McGinn 1992 in (Rechtin & Maier 1997)). The support should be scientifically based (Ali Khan & Wallace 2003) or based on profound industrial experience. This assures functionality of the support as well as efficiency. Moreover, the support has to be adaptable to the specific context of the development project or it has to be universal and comprehensive, so that it can be used in various different projects and as general support in different phases of a project.

The new support has to be applicable for the development of products for changing environments. As mentioned in Section 2.4.2 either flexible products or robust products can be designed for this specific context. In order to form a comprehensive solid basis the support is derived from the approaches, ideas, methods and tools that have been described in Chapter 3.

4.2 Design Guidelines

Engineering design guidelines are a rich repository of design expertise. They support the decision process by providing rationale and by suggesting what actions to take, what issues to address, and the potential consequences (Charlton & Wallace 1997). They are among the simplest, oldest, and best known design tools supporting the product development process (Pahl & Beitz et al. 2007).

Many product developers are familiar working with guidelines. Thus, acceptance is facilitated, training period shortened, memorability increased and application eased. Moreover the design guidelines are cheap to create in an adequate form, easy to distribute and cheap to purchase, as no costly technology is necessary.

4.2.1 **Definition of Design Guidelines**

Design guidelines are one of the main sources of explicit knowledge on the practice of design (Dieter 1991). The main sources of design guidelines include literature, direct experiences of practicing developers and established design practices of engineering organizations. The differences in terminology used during design and design research can often lead to misunderstanding (Edwards et al. 1993). To overcome this problem, the term guideline, design guideline respectively, is defined as follows (Edwards et al. 1993): A guideline is a principle put forward to set standards or determine a course of action. Design guidelines are explicit knowledge of the practice of design. Design guidelines are more often found where the course of action is not clear, but where one particular action has been found to work well in the past. Design guidelines, therefore, are more frequently specific to a specific domain and can represent a wide range of experience in the use of existing technology.

The term guideline is often used to collectively mean guidelines, principles, axioms, roles, aids, tips, hints, suggestions, methods, etc., in advising good mechanical engineering design practice (Edwards et al. 1993). According to Van Wie (2002) a guideline "is a heuristic in that it is a recommended action that is not guaranteed to work although it generally prescribes a useful action for some condition." He defines: "A guideline is a specification for some recommended action X on data Y that generally results in output Z." This is the way guidelines are understood in this work and thus Van Wie's definition is used here.

In a review on engineering design guidelines Nowack (1997) highlights two significant issues: the abstraction level of the guideline, and its purpose. The level of abstraction dictates the number of guidelines at that level and the content of each guideline at this level (see Figure 4-1).

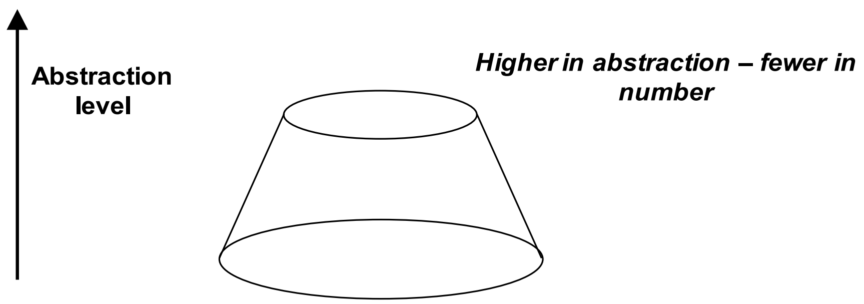


Figure 4-1 Guidelines and abstraction level (Van Wie 2002)

A high abstraction level has the advantage of broad application. Only a few guidelines have to be maintained, understood, learned and applied. However, the support is low; application may be difficult and specific cases may not be addressed. In contrast, a low level of abstraction provides guidelines that are easy to execute. On the downside of a low abstraction level is the lack of generality. Moreover, a higher number of guidelines is more difficult to maintain, understand, learn and remember (Van Wie 2002).

Figure 4-2 is a classic example of an engineering design guideline. It consists of brief comments, giving advice to the product developer. There are two illustrations for each guideline. They show a negative and a positive example to enhance the understanding of the guideline. Usually the examples are as general as possible and as specific as necessary for understanding the text. In this example further information is given: The first row indicates at what specific procedure the guideline aims (handling), the second row indicates how the aim can be achieved (e.g. reduce weight) and in the third row illustrations of an unfavorable and a favorable example are given to ease understanding and increase memorability. The last row consists of comments further explaining the guidelines and their applications and limitations.

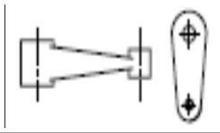
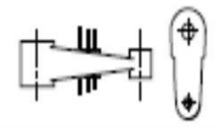
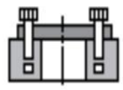
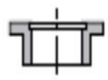
Aim	Design criteria	Examples: Unfavourable	Examples: Favourable	Comments
Handling	Define propper gripper surface			Use parallel gripper surfaces with proper positioning in reference to the center of gravity.
	Reduce weight			Use synthetic material. The weight should not be extremely low.

Figure 4-2 Example of design for manufacturing guidelines (Pahl & Beitz et al. 2007)

4.2.2 Requirements on Design Guidelines

According to Van Wie (2002) design guidelines have to be practical and easy to use, therefore effective. The effectiveness can be thought of as how much effort is required on the part of the product developer to apply the guideline successfully. It is about how well the guideline supports in terms of quality and quantity of results. This effectiveness highly depends on the context, which consists, among other things, of the complexity of the operation, the required time to execute a specific task, and the amount of resources required for this operation. Moreover Van Wie points out that a guideline has to be technically complete and comprehensive.

Finally, any support has to be consistent with the product requirements and customer needs. Van Wie explains this with an illustrative example: "consider a guideline such as "make it lightweight." The mass or weight is relevant to both a heavy machine tool and a spacecraft, but the guideline is much more consistent with the requirements of a spacecraft since the spacecraft must be lightweight whereas the machine tool places relatively less emphasis on weight." The last issue, however, is very much dependent on the product and can hardly be taken into consideration when formulating guidelines of general validity. However, the developer using guidelines during a product development project should be well aware of this topic.

Several requirements for illustrated guidelines can be defined in order to provide proper usage, improve understanding and minimize misinterpretation. Van Wie (2002), Campbell et al. (1998) and Mayer & Gallini (1990) provide the following suggestions for the format of guidelines:

- Be graphic based with supporting text.
- Use texts brief, clear and understandable as possible.
- Balance supportive function of the illustration with complexity of the text and its information.
- Make use of (self) descriptive illustrations and showing and naming all components of the system and their correlations.
- Present guideline knowledge in a consistent and concise manner.
- Be independent from the product development methodology in which the guidelines are applied.
- Provide explicit design guidance to show how to apply the design knowledge.
- Include text information that is brief, highly organized and tightly structured and have succinct text where text is needed.
- Include a succinct tactical level action statement (textual).
- Include brief rational for the design knowledge.
- Balance supportive function of the illustration with background knowledge of the beholder.

In the interpretation of Van Wie (2002) – in contrast to many others – a guideline can consist of a series of steps. In this case the guideline has to present each step clearly at the design action level (see Figure 4-1), including the recommended execution. While most guideline illustrations aim at showing the implementation of the guideline as general as possible in order not to bias the developer, Van Wie asks for graphical illustrations of guideline applications to a real product.

In literature product development guidelines are explained using graphics showing either the principle or an example of its application (see Figure 4-2). Awkwardly many of the approaches and the including guidelines mentioned in Chapter 3 are only textual and thus more difficult to understand (Weidenmann 1991). Using the well known graphical product development guidelines, as example, the newly developed guidelines and the collected textual are transferred into graphical ones (see Section 4.3). Because guidelines are instructions, it is important to look into instructional design for suggestions to achieve better understanding.

Instructional design deals, among other topics, with the analysis and development of graphical illustrations for teaching material. Illustrations can achieve different functions (Levin et al. 1987). They can make reading the text more attractive, introduce people, things and plots and they can help the reader to remember the key information better. Illustrations can have the functionality to organize the connected structures and thus make the text more understandable.

Levie & Lentz (1982) point out that illustrations can help the reader to understand the learning materials when they already have background knowledge as well as when they do not have any knowledge related to the topic. Especially for understanding complex coherences, illustrations support the understanding and learning process more effectively than textual explanations only (Mayer & Gallini 1990). If learning time is limited, the simple graphic illustrations, as to be found in the standard literature of engineering design (e.g. Pahl & Beitz et al. 2007), are very supportive. Only if there is a huge amount of time for watching more detailed and realistic illustrations are more effective (Dwyer 1972).

Colors can have positive as well as negative effects in illustrations. They allow the beholder to identify different elements and understand the coherences between the single illustrations. Using too much color in one illustration can have negative effects on understanding and memory due to increasing complexity.

Different requirements which have to be fulfilled in order to effectively support the understanding of scientific texts with help of illustrations can be derived from the study of Mayer & Gallini (1990):

- The text has to be clear and understandable.
- The supportive function of the illustration has to be balanced with the background knowledge of the beholder.
- The supportive function of the illustration has to be balanced with the complexity of the text and its information.
- The illustrations have to be (self) descriptive: showing and naming all components of the system and their correlations.

4.2.3 **Application of Design Guidelines**

"Designing, like any problem solving process, involves making decisions" (Edwards et al. 1993). Design guidelines aid this decision making process, they help to cope with specific situations (Pahl & Beitz et al. 2007). They are empirical and based on intuition and experience. These guidelines are either already known by the developer, being triggered by tasks or events during the design process, or obtained from reading relevant texts or talking to colleagues. The latter tends to be more difficult and slower to retrieve, but in combination with the former tends to stimulate the thought process. The management of this process is difficult to control, particularly during the conceptual design phase, where information is limited and abstract thinking is dominant. From embodiment to detail design, the amount of specific information increases rapidly as a single concept is configured and optimized and provided with sufficient information (Edwards et al. 1993).

Design guidelines exist for all stages of the product development process (Figure 4-3). Benefits are mostly achieved after product development, e.g. in manufacturing and in the use phase. Benefits during the early phase are not yet as well supported scientifically.

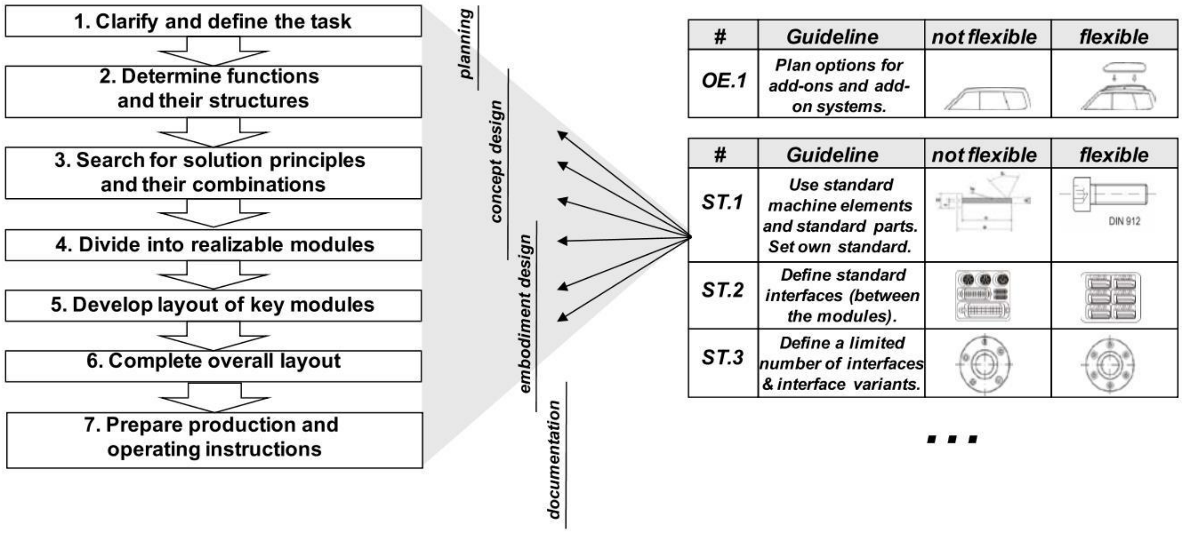


Figure 4-3 The application of design guidelines in the context of the product development process

Guidelines can only be applied effectively when developers have easy, context sensitive access to relevant guidelines. However, simple access is difficult, particularly with a large number of guidelines covering multiple topics, as found by Ackers et al. (1995) cited by Charlton & Wallace (1997). Hence, the number of guidelines should be limited. Clustering the guidelines might help to ease handling and allows a quick overview as well.

4.3 Guidelines for Developing Flexible and Robust Products

This work is to contribute to both, first see what more guidelines can be formulated to support the development of products for changing environments and thus, second contribute to the concept of product flexibility. The following sections describe how this is achieved by collecting existing guidelines, deriving and newly illustrating existing guideline-like ideas. Moreover the new guidelines are clustered and several guideline examples are explained.

4.3.1 Deriving New Guidelines

In general new guidelines are derived from industrial practice and transferred to scientific literature (e.g. Pahl & Beitz et al. 2007). Here the basis is a comprehensive literature study (Chapter 3). Thus, it is a consolidation of various approaches, which have either been proven in industrial practice, are formulated on the basis of research, are based on product analysis, or are a combination of several ideas. These approaches are merged to a new set of guidelines labeled Design for Flexibility (DfF) guidelines, because flexibility is one of the most important issues for dealing with changing environments (Figure 4-4).

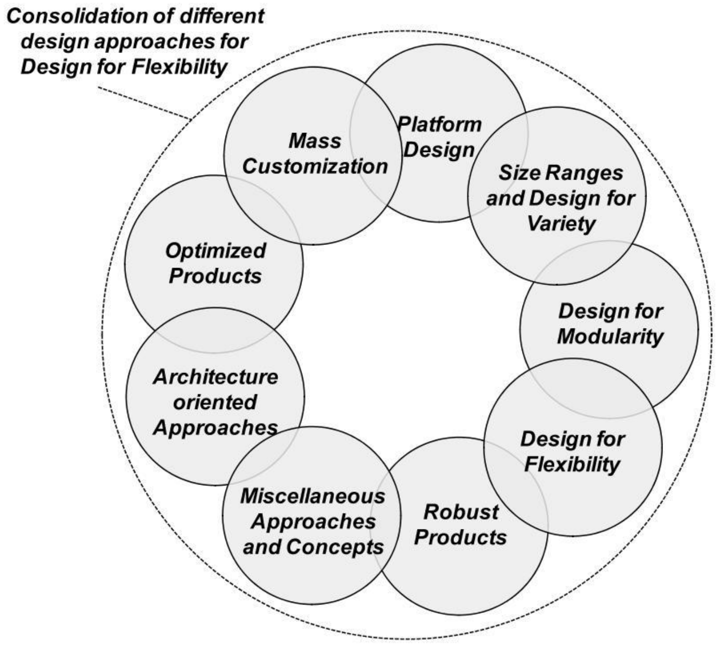
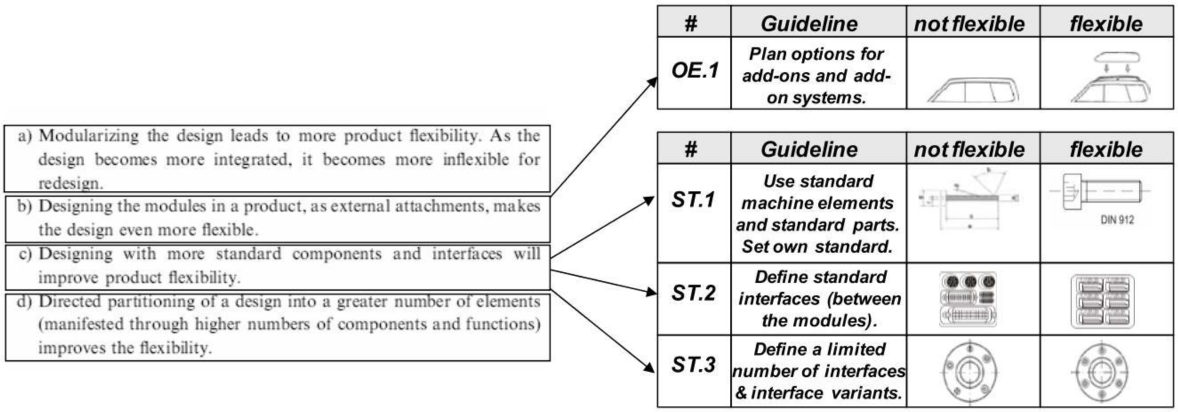


Figure 4-4 Consolidation of different design approaches for Design for Flexibility

Design guidelines were chosen as support for the development of products for changing environments because of their easy application and creation. Primary guidelines for an initial study were generated, applied and discussed (Bischof & Blessing 2007). Positive feedback in the study as well as during discussions in academia encouraged the guideline idea.

The textual guidelines, which can be found in the approaches mentioned in Chapter 3, are translated into graphical ones with help of the findings of instructional design (see Section 4.2.2). The existing guidelines are checked and adapted for a clearer and better understanding. The illustrations are self-descriptive avoiding textual explanation in the graphics. As watching time is mostly limited, the illustrations are designed as simply as possible. All illustrations are black and white only. Additional colors are avoided as they increase complexity. This way they also better fit into the context of guidelines engineering design literature, which are all black and white only. Basic technical knowledge on the beholders' side is assumed (Bischof & Blessing 2008).

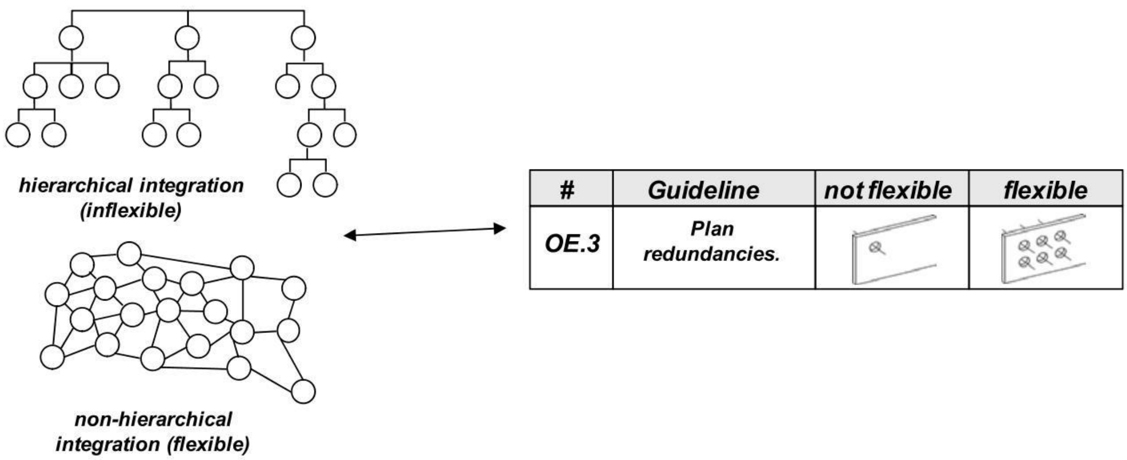
Some approaches formulate design guidelines for the design of flexible or robust products (e.g. Palani Rajan et al. 2005). Figure 4-5 illustrates how they are translated from the original text (a) into new ones with the classical layout (b) consisting of a brief instructive text and two simple illustrations. One picture shows a non favorable example of guideline application and the other one a favorable example. The two examples are labeled as *non flexible* and *flexible*. Even though not all guidelines aim at developing flexible products, but rather on robust products to handle changes in the environment, no distinction will be made in the new set of guidelines. The term flexible is understood more generally as handling changes in the environment. The guideline text is rephrased to fit a common structure. The examples are as general as possible, yet comprehendible. All examples are chosen from various industrial branches, but can be understood with basic and common engineering knowledge.



(a) original text from Palani Rajan et al. (2005) **(b) newly derived guidelines (excerpt)**

Figure 4-5 Example of direct guideline derivation

An example of a more abstract derivation of a new DfF design guideline from an existing concept is illustrated in Figure 4-6. Schulz & Fricke (1999) suggest using a non-hierarchical integration across the product (down part of Figure 4-6 (a)) to enhance the product flexibility rather than hierarchical integration (upper part of Figure 4-6 (a)). Through analyzing this concept it becomes obvious that the non-hierarchical integration maintains the main functionality because of other back-up connections in case one connection fails. The back-ups can be interpreted as redundancies, as more than one connection between the parts is present. Thus, in a more general (and easier to understand) concept the new guideline sets includes the guideline “Plan redundancies” in order to enhance product flexibility or robustness for changing environments. Again, the new guideline consists of a brief instructive text and two illustrations one with an unfavorable application and one with a more favorable application of the guideline.



(a) abstract guideline from (Schulz & Fricke 1999) **(b) newly derived guideline**

Figure 4-6 Example of abstract guideline derivation

A slightly longer text is formulated to explain the application of the guideline and the underlying idea (Figure 4-7). This text is only for initial explanation. It is not necessary to reread this text every time the booklet is checked for possible guideline application. Thus, understanding of the guidelines can be more profound and time is supposably reduced when using the booklet in order to stimulate the thought process, confirm existing solutions, refresh memory, and get new or alternative ideas. This way the application can be kept simple and less disruptive. Similarity to well known guidelines (e.g. Pahl & Beitz et al. 2007) can reduce learning effort and reservation of the users.

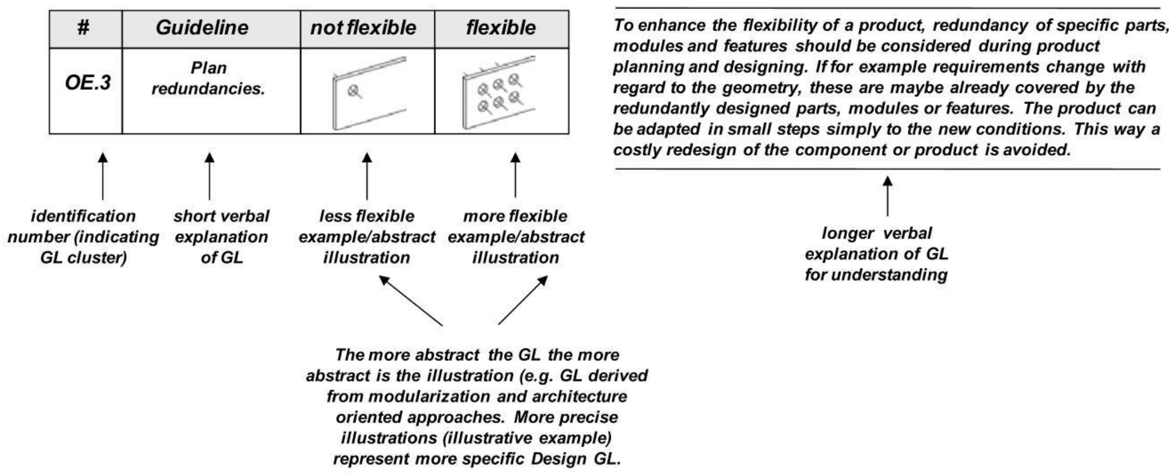


Figure 4-7 Explanation of guideline example

The analyzed literature leads to a set of 34 new design guidelines. Most of the guidelines are based on more than one reference. The derivation of the guidelines is often indirect and abstract. In Table A2 - 1 the single design guidelines are mapped with the analyzed references. An excerpt of the full table is shown in Table 4-1 below. The filled bullets indicate a relatively direct correlation of the guideline and the reference. The open bullets represent a less direct mapping of the single guidelines and the analyzed references.

Table 4-1 Mapping derived guidelines with references – excerpt only, full table in Table A2 - 1

guidelines	modularisation									inherent flexibility						DA		ST				extended use						over-engineering						
approach	MD.1	MD.2	MD.3	MD.4	MD.5	MD.6	MD.7	MD.8	MD.9	IF.1	IF.2	IF.3	IF.4	IF.5	IF.6	DA.1	DA.2	ST.1	ST.2	ST.3	ST.4	EU.1	EU.2	EU.3	EU.4	EU.5	EU.6	OE.1	OE.2	OE.3	OE.4	OE.5	OE.6	OE.7
product flexibilisation																																		
Engel & Browning 2006												○		○	○	○	○	○		○														
Fricke & Schulz 2005	●	●				●		●		●	●	●						●		●		●						●	●	●	●	●	●	●
Nilchiani et al. 2005																						○	○	○	○	○	○	○	○	○	○	○	○	○
Palani Rajan et al. 2003	●	●	●	●		●												●		●												●	●	●
Palani Rajan et al. 2005	●	●	●	●		●												●		●									●		●	●	●	●
Sanchez & Mahoney 1996	○	○	○	○	○	○			○									○	○	○	○													
Schulz & Fricke 1999	●	●				●		●		●	●	●						●		●								●	●	●	●	●	●	●
Schulz et al. 2000	●	●				●		●		●	●	●						●		●		●						●	●	●	●	●	●	●
Smith 2007	●	●	●	●	●	●	●	●	○													○	○	○	○	○	○							
Thomke & Reinertsen 1998			●	●		●																												
Van Wie 2002	●	●	●	●		●												●		●												●	●	●

● = guideline derived
○ = guideline idea recognizable
all references with no relation to the derived guidelines excluded

In sum, 34 guidelines to support the design of products for changing environments have been formulated. In order to ease understanding, optimize memorization and provide a fast overview all 34 guidelines are clustered in six clusters, which are listed as follows:

- Decoupling and Modularization (MD)
- Inherent flexibility (IF)
- Easy (dis-)assembly (DA)
- Standardization (ST)
- Extended use (EU)
- Over-Engineering (OE).

All six clustered are explained in detail in the following sections. The explanations include how the guideline cluster is understood, where the guidelines are derived from and what they aim for. Moreover, an example from each cluster is given and possible, specific forms of applications for the guidelines.

4.3.2 Decoupling and Modularization (MD)

The first cluster of guidelines is the Decoupling and Modularization (MD) cluster. It consists of nine collected, derived, and newly illustrated guidelines (see Table A2 - 2). These guidelines aim at subdividing the product. In order to enhance flexibility the coupling between the parts and modules should be designed as loosely as possible. If achievable the single modules of the product should be autonomous – meaning working independently from the other parts and modules of the product. Thus, they are not affected by changes on the product and do not cause troublesome effects themselves, when being changed or replaced. Differential design[8] is favored over integral design[9], because products with differential design usually consist of higher number of parts that are loosely coupled. When developing the product (modular) up scaling has to be considered to allow easy functional and structural extension of the product after fielding without complete redesign.

The guidelines consolidated in Decoupling and Modularization (MD) are derived from various approaches like Design for Adaptability (Hashemian 2005), Design for Modularisation (Erixon 1998), Design for Changeability (Fricke & Schulz 2005) and Design for Flexibility (Palani Rajan et al. 2003). Moreover Suh's independent axiom (Suh 1998) can be considered fundamental for this cluster. For all references from which these guidelines are derived see Table A2 - 1.

Several different effects behind these guidelines enhance either the flexibility or the robustness of the product. By applying the guidelines, the changing of parts is eased; the necessary effort for the changing procedure reduced. The product can easily be extended. New functions (as possibly demanded in future environments) can be added fast and easily. Moreover, new and alternative configurations can be realized without effort. The development of new products is simplified as the existing architecture and modules can be taken without much redesign. Up scaled versions of the product can be generated easily in order to fulfill changing requirements and offer higher value to the customers. Challenging avalanche effects of changes (during development and on the material product) are interrupted. Changes are bounded to single parts or modules without affecting the whole product.

Figure 4-8 below shows an example of a guideline from the Decoupling and Modularization (MD) cluster. The guideline is presented in the classical format as mentioned in Section 4.3.1. The guideline MD.1 "Minimize the internal connections. Use bus systems." aims at enhanced product flexibility and robustness at the same time. As described at the right side, by implementing this guideline in a development project the product can be modified and reconfigured more easily than with an integral architecture. Thus on the one hand flexibility is improved. On the other hand the bus architecture is less sensitive to external disturbances and changes. Single parts and modules can be disconnected and redesigned without affecting the functionality of the rest of the product.

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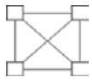
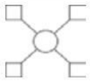
[8] *Differential design* (differential construction) is defined by Pahl & Beitz (2007) as „the breakdown of a component (a carrier of one or several functions) into several easily produced parts."

[9] *Integral design* (integral construction) is defined by Pahl & Beitz (2007) as „the combination of several parts into a single component."

#	Guideline	not flexible	flexible
MD.1	Minimize the internal connections. Use bus systems.		

Minimizing the internal connections and making use of bus systems allows easy exchange of product parts during the whole life cycle. The less a part or a module is connected with other parts of the product the less the exchange or change of this part affects the rest of the product negatively. This way later changes can be implemented easier.

Figure 4-8 Guideline example for Decoupling and Modularization (all MD guideline see Table A2 - 2)

Modular design is the main issue of this guideline cluster. Hölttä & Salonen (2003) suggest three different methods that can be used alternatively to support this step: first, the function structure heuristic method (Stone et al. 2000, Zamirowski & Otto 1999), second, clustering with help of the design structure matrix (DSM), and third, Modular function deployment (MFD) (Ericsson & Erixon 1999). Erixon (1998) gives a rule of thumb for optimal modularity: The number of modules in a product should be around the square root of the number of parts. For example, a product made from 100 parts should consist of about 10 modules.

The figure below (Figure 4-9) illustrates a trolley-car, where the application of several guidelines of the Decoupling and Modularization cluster is apparent:

- The trolley-car is built with a modular architecture (MD.3).
- The trolley-car can be made up of several modules (MD.4).
- Modules are based on functional clusters (MD.5).
- The trolley-car can be scaled (MD.7).

Figure 4-9 Modular designed trolley-car (Pahl & Beitz et al. 2007)

4.3.3 Inherent Flexibility (IF)

Some design solutions are more flexible than others. They contain a flexibility in itself, which is here called Inherent Flexibility (IF). Inherent Flexibility is achieved by integrating flexible and change tolerant design features and machine elements into the design. Moreover, flexibility is enhanced by aiming for universal designs[10]. Further guidelines demand self-healing and self-adjusting technologies and solutions. The option of flexible assembly order enhances product flexibility as well. Using parametric design (e.g. when working with the CAD system) has a kind of inherent flexibility as well. In general, software can be changed easier than hardware. This can be understood as an inherent flexibility of software solutions. Thus, one guideline asks for software instead of hardware solutions to improve the product flexibility. In total six guidelines are formulated to support the design making use of inherent flexibility (Table A2 - 3)

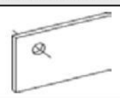
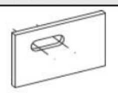
The six guidelines in the Inherent Flexibility cluster are derived from various approaches. Among these approaches are Design for Adaptability (Hashemian 2005), Robust and Universal Design (e.g. Chen & Lewis 1999) as well as general comprehensive design methodologies (Pahl & Beitz et al. 2007). In Table A2 - 3 all Inherent Flexibility guidelines are mapped with the references to which they can be allocated.

The effects, on which the Inherent Flexibility guidelines are based, are diverse. Even though product flexibility is hard to capture and rather challenging to measure (see Section 2.4.5) it is obvious that some technologies are more flexible than others. Implementing these technologies into new products in general increases their flexibility. Universality results in robust solutions. In the same way, flexible design features and machine elements lead to robust parts. By applying these directly the likelihood of changing the product is smaller, even when changes in the product environment occur. Self-healing and self-adjusting solutions ease or avoid the changing procedure on the material product. This way less work is necessary for reassembling after changes are implemented on the material product. A flexible assembly order eases changing procedure in case of changes without the whole product having to be disassembled.

The figure below exemplarily shows one of the six Inherent Flexibility guidelines (Figure 4-10). The guideline IF.1 “Use flexible and change-tolerant design features and machine elements” can be considered tautological, if aiming at flexible product design. However, the guideline reminds the product developer to think about flexible design features and implement these in the new product. These features and machine elements are not necessarily more complex or more expensive than other ones. However, they increase the product flexibility and can provide higher value to the

[10] *Universal designs* are understood as design solutions that can be used for the same purpose in different environments without changing the product like e.g. an adjustable wrench.

customer and help to handle new and alternative adjustments, which are caused by external and internal changes to the product.

#	Guideline	not flexible	flexible
IF.1	Use flexible and change tolerant design features and machine elements.		

Design features, for example boreholes, should be designed such that later changes in the configuration can be implemented with little effort. This can for example be realized by making use of slot holes or oversized holes. This way the part or product does not necessarily have to be changed, when later requirements slightly differ or demand adjusting.

Figure 4-10 Example for Inherent Flexibility guideline

The Inherent Flexibility guidelines can be applied during the whole development process like all other guidelines (Figure 4-3). However, the product developer has to be aware that sometimes application is most beneficial in the early phases of the product development process (e.g. IF.6 “Implement software instead of hardware solutions”), while others are applied very beneficial in the later phases, when detailed features are designed. An example for the possibility of later application is guideline IF.1 shown in Figure 4-10. When designing an angle bracket as shown in Figure 4-11, the decision of whether to make use of slot holes or round ones can be left open until the embodiment design phase. This is a rather basic example; however, it still explains how flexible and robust design features can look like and how they are implemented in a product without additional work or costs, when the machine part is manufactured in a stamping process.

Figure 4-11 Angle bracket with two slot holes for universal fitting without redesign, new drilling, etc.

4.3.4 Easy (Dis-) Assembly (EA)

Another cluster of guidelines is named Easy (Dis-)Assembly (EA) and it consists of only two guidelines (Table A2 - 4). They focus on the basic principles of Design for Assembly. The first one is about planning definite connection and separating mechanisms. The second one suggests placing parts that are subject to regular wear and tear on the outside of the product or at easily accessible places. Both guidelines aim at easing the assembly and disassembly process. Many more guidelines exist within the Design for Assembly area.

Both guidelines for Easy (Dis-) Assembly (EA) are derived from classic Design for Assembly, respectively Design for Disassembly (e.g. Andreasen et al. 1988). All suggestions on Design for Assembly can be applied when developing products for changing environments. However, the two selected guidelines represent the core idea of eased assembly processes; they can also be interpreted as representatives of the numerous Design for Assembly guidelines. In Table A2 - 1 both Easy (Dis-) Assembly (EA) guidelines are mapped with the references to which they can be allocated.

Changes on the material product usually require a (partly) disassembling of the product. After changes are implemented, and parts have been reconfigured the product has to be reassembled. Thus easing the (dis-) assembly procedure reduces the effort of the change procedure; changes can be implemented more easily. As illustrated in Figure 4-12 changes can be implemented that are cost and time efficient when Design for Assembly is applied.

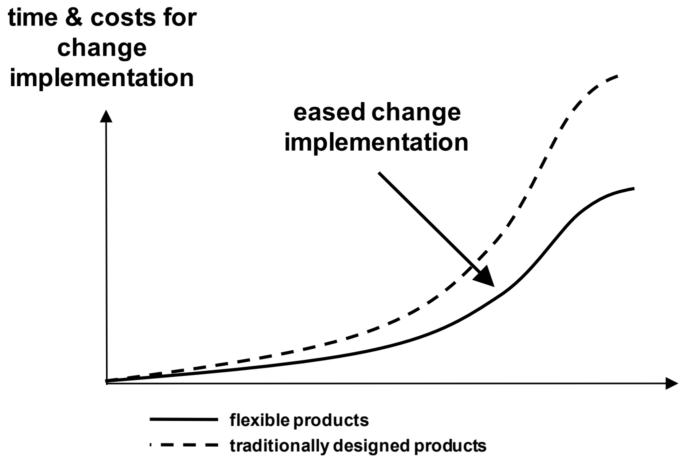
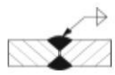
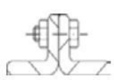


Figure 4-12 Increased efficiency of change implementation by applying the Design for Assembly (based on Fricke 2006)

The figure below illustrates the first of the two Easy (Dis-) Assembly (DA) guidelines. The guideline DA.1 "Plan definite (dis-) connecting devices and consider disconnecting from the beginning" is shown in Figure 4-13 below. The left illustration in the guideline shows a connection, which is rather difficult to dis- and reassemble (welded joint), when external changes make disassembly, adaption and reassembly necessary. The right illustration shows a bolted joint, which is easier to dis- and reassemble and hence a favorable solution to enhance the product flexibility. In Design for Dis-/Assembly literature screws are not always highlighted as positive examples, as there are solutions that can be assembled and disassembled with less effort than necessary for a bolt and nut connection. However, it is more flexible, well known to all engineering designers and thus easy to understand and remember.

#	Guideline	not flexible	flexible
DA.1	Plan definite (dis-) connecting devices and consider disconnecting from the beginning.		

In order to enhance product flexibility inseparable fasteners should be avoided. Explicitly defined fasteners and disconnecting mechanisms ease the changeability of single parts and modules. Moreover, new products can be realized by combining the parts and modules in new configurations. Early planning of fasteners eases the implementation of change in the later phases of the product life, as usually a (partly) disassembly of the product is necessary for exchange process.

Figure 4-13 Guideline example for easy (dis-) assembly

Both (Dis-) Assembly guidelines are very much understood as a means to create awareness about taking the dis-/assembly process into account when developing a new product. More guidelines (and other support), which support the Design for Assembly can be used by the developers, if considered necessary. The picture below shows a cable strap that can be opened and reused (Figure 4-14). Thus disassembly is eased and can be carried out without tools. The dis-/assembly procedure is less laborious and the product can be considered more flexible as it is better prepared to handle changes that occur during its life cycle.

Figure 4-14 Cable strap that can be opened and reused

4.3.5 **Standardization (ST)**

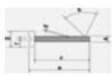
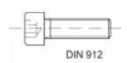
The fourth cluster of design guidelines consists of four guidelines summarized under the name Standardization (ST). The first guideline proposes the use of standard parts, standardized parts, or setting own standards. Two guidelines focus on the interfaces between the parts and between different modules of the product. One reminds the developer to use standard interfaces, the other to limit the number of different types of interfaces. The last guideline supports the design of modules in a way that identical modules can be used in different products. All guidelines can be found in Table A2 - 5 in the appendix.

Standardization is very common in engineering design and is supported by national and international standards (e.g. DIN, ASME, ISO). The guidelines used for the new Design for Flexibility guideline set are derived from various references, listed in the appendix in Table A2 - 1.

For instance, Hashemian (2005) suggests increasing the compatibility among parts and modules through the standardization of products and their interfaces. Standardization is applied in all engineering disciplines. Hence, guidelines can be found and derived from all the different approaches described in Chapter 3, which represent various disciplines and branches.

Making use of standards, standard parts and machine elements, and setting own standards support the design for changing environments. The product becomes more flexible. With the application of standards, the exchange of parts and modules with other parts and modules is eased. Future exchanges of single product parts, modules or machine elements can be carried out easier as well, as future parts follow the same standard. The change procedure is simplified: With a limited number of standard parts, the procedure is easy to learn and easy to repeat; fewer tools are needed. Developing parts and modules in a way that they can be used for other products as well reduces the effort of developing further products. Creating a higher variety in the sense of a product family and generational development is also supported (Figure 3-11).

The figure below exemplarily shows one of the four guidelines supporting the design for flexibility by applying for standardization (Figure 4-15). The chosen guideline ST.1 "Use standard machine elements and standard parts. Set own standards." describes the basic idea of the whole set. Instead of developing every part from scratch (left illustration) the use of a standard part (here screw, DIN standard 912 (1983)) is proposed in the right illustration. Standard parts and machine elements are tested, easy to purchase, and can be used everywhere. Thus, replacing these parts or disassembling the product and assembling are simplified. Using standard parts has positive effects on logistics and manufacturing costs as well. In this way a greater product variety or product family can be developed and provided efficiently.

#	Guideline	not flexible	flexible
ST.1	*Use standard machine elements and standard parts. Set own standards.*		

Using standard machine elements and defining company standards for parts and modules eases the exchange of parts and modules, if the other products are based on the same standards. Later upgrades are eased. Development costs can be minimized due to multiple use of modules and products. The (dis-) assembly procedure is eased, if standard machine elements are used; no special tools are needed to implement changes on fielded product.

Figure 4-15 Guideline example for standardization

The guidelines, clustered under Standardization, can be applied during the whole development process like all other guidelines (Figure 4-3).More specific advice than that provided by the guidelines cannot be given. How many standards and standardized parts should be applied has to be defined by the individual developer for every product. The decision is based on specific project and product information, context factors, experience and abilities of the product developer.

Setting standards on a more abstract level can be achieved for instance by applying the platform strategy approach (see Section 3.5). These decisions are made by people responsible for company strategy or product portfolio. When applying standards a reasonable balance between strictly sticking to these and working more freely without them has to be found.

Figure 4-16 below illustrates the multiple use of a standard machine element (a socket head cap screw) on one product (a bicycle) to mount different parts. This not only reduces production and purchasing costs due to higher volume and simplified logistics, but also simplifies replacement (change procedure) of those elements that are connected. Replacement parts can easily be purchased in future, e.g. after a change. Such a product can be considered more flexible or better prepared for changing environments than a product using many different parts or custom parts for the same purpose.

Figure 4-16 Multiple use of a standard machine element in one product

4.3.6 **Extended Use (EU)**

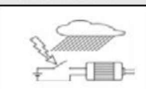
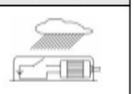
Six guidelines are collected and clustered as Extended Use (EU) guidelines. They are about anticipating future functions that are not yet mentioned as specific requirements. It is about imagining, what the user might ask for and integrating these functions in the first product. In this way the product is more robust and thus able to cope with changing environments; early upgrades and new releases are made less probable. Moreover, the product has to be designed in a way that additional future functions can be implemented easily. The Extended Use guidelines also support the development of products that are usable in different environments and under different conditions. This includes being suitable for a great variety of users, e.g. by universal product design. Extended Use can be interpreted as a theoretical exaggeration of the initially planned product use. Thus, the product can be designed matching various conditions and handle future changes of its environment.

The guidelines supporting the Extended Use are derived from various references. Besides the approaches aiming at robust design (see Section 3.2), the ideas of flexible product design (see

Section 3.4) have also been used as a basis for the new guidelines (e.g. Nilchiani et al. 2005, Smith 2007). Hashemian (2005) recommends "the extension of utility" of a product; he proposes "the adaptation of a product as one way of extending its utility." The product is useable even when its environment (including the user) changes.

The six Extended Use guidelines aim at anticipating different conditions, different kinds of usage and functions, future requirements, further markets and customers, and different contexts and environments for the product. Thus, the initial product requirements list is extended. Designing the product to match this extended list will make it more robust. As explained before, this way the product remains usable even if its environment changes.

Figure 4-17 shows an example of a guideline from the Extended Use (EU) cluster. Guideline EU.2 "Make products usable in different environments" reminds the product developer to think of different environments the product can be used in. The two illustrations in the guideline show an electric product not being able to be used outside in rainy environments as an inflexible, respectively weak – not robust, product. The illustration showing the flexible (respectively robust) example shows the same product, but with a cover to handle wet environments. Thus, the developers are reminded to think of possible, not initially required conditions for the product. Even though the illustrations refer to rain and humidity they bring to mind other possible new environments like extreme heat, cold, pressure etc.

#	Guideline	not flexible	flexible
EU.2	Design parts to be used in various conditions and environments.		

Already in the planning phase different environments for product application should be considered, such as a wide range of temperature, pressure, humidity, etc. Materials and design can be chosen to cope with all these environments. Furthermore, product robustness is enhanced.

Figure 4-17 Guideline example for extended use

The illustration below shows an example of a product, where additional functions are implemented (see Figure 4-18). The left picture shows a pocket knife with a rather limited number of functions. The picture in the middle shows a knife that has several more functions. These functions can either be required by the customer or thought of by the developer. The third picture is a highly exaggerated version of this idea, which makes the whole product almost unusable.

Figure 4-18 Product example for extended use – exaggerated Swiss army knife

The example shows that the idea of extended use should not be overdone. The product developers should start from existing features and functions and then try to derive new ones. This can be done by thinking of other users, environments, etc. with the help of various creativity methods.

4.3.7 Over-Engineering (OE)

The last cluster named Over-Engineering (OE) consists of seven guidelines. The guidelines are similar to Extended Use (see Section 4.3.6), but are more focused on physical parts, modules and machine elements instead of functions. There is a trend that requirements are getting even higher. For example the capacity of a computer hard disk is dramatically increasing every generation; the average engine power of cars has increased constantly over the last decades. The guidelines presented as Over-Engineering (Table A2 - 7) aim at forecasting these kinds of trends and at developing products that less likely need changing when requirements get higher. The products can be understood as more robust (see Section 2.4.2) and can remain functional even when their environments change. The seven guidelines support various aspects of over-engineering: They are related to load and stress, to power and energy, to space and geometry. Moreover, they remind of possible future changes and propose the use of technology that is far from obsolete, make use of add-ons, redundancies and integrate buffer zones in the actual design to have space for possible future upgrades.

Ideas similar to the one in the guidelines of Over-Engineering can be found for all approaches presented in Chapter 3. Most of them are derived from the Design for Flexibility approaches (see Section 3.4) as shown in Table A2 - 1 in the appendix. This again shows the strong correlation of flexibility and robustness, as over-engineering aims more at the products' robustness than at their flexibility. The idea of anticipating future environments and markets is often derived from product life cycle approaches (e.g. Fricke & Schulz 2005). By taking into account the whole product life and especially anticipating possible changes in its future use phase, additional and stricter requirements can be identified. Implementing these in the initial product design is the classical way of over-engineering.

The basic idea behind the Over-Engineering guidelines is to avoid future changes by analyzing current environments and requirements, pushing the requirements further and anticipating future environments. This strategy of avoiding future changes is illustrated in Figure 4-19 below. Over-engineering reduces the number of changes in the product compared to the traditional design strategy.

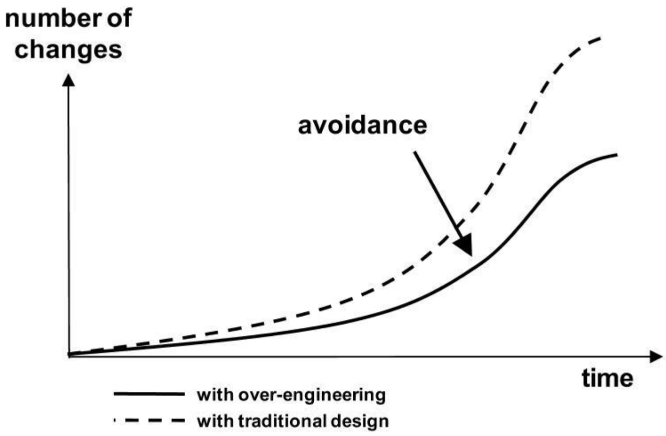


Figure 4-19 Avoiding later changes (based on Fricke 2006)

One example of a guideline from the Over-Engineering (OE) cluster is shown below in Figure 4-20. The guideline OE.2 "Create buffer zones" supports the flexibility or robustness of the product not directly by anticipating future environments and integrating future requirements and functions initially, but by developing the product in a way that future changes can be implemented more easily. Space is left free for future upgrades. This is using a housing of an electric engine without buffer zones (not flexible) and with a buffer zone (flexible). The empty space in the housing can be used to implement future changes, like bigger engines, additional functional devices as electronic control systems, brakes, or gears. Already having the space reduces the number of parts, which have to be changed, when new functions have to be implemented. The effort in the change process is reduced, the product better prepared for different requirements and thus more flexible (robust respectively).

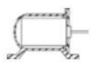
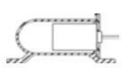
#	Guideline	not flexible	flexible	*Creating buffer zones enhances the flexibility of a product, as these allow to accommodate larger parts and modules without redesigning the whole product.*
OE.2	*Create buffer zones.*			

Figure 4-20 Guideline example for over-engineering

The guidelines are used to remind the product developers of the over-engineering concept and generate new or alternative ideas. Related to anticipating future changes and over-engineering the product Hashemian (2005) advises completely freely imagining new requirements, but to build up on existing ideas, solutions and trends. It is more about extrapolating known functions and requirements rather than search for new ones. Therefore, one advice for applying the Over-Engineering guidelines is to learn from the past. However, one should not overdo it, otherwise the product can become too expensive, too heavy, too big, etc. and thus less competitive. A simple example, in which Over-Engineering guidelines have been applied, is shown below in Figure 4-21: Often fridge door handles and the doors themselves are designed in a way that the handle and the hinge can be mounted in two different ways, allowing the door to be opened to the left or to the right. In this way the fridge better fits to its kitchen environment, and can even be adapted if necessary. This flexibility is most often achieved by designing the handle symmetrically and preparing the door plate with mounting options on both sides. This can be understood as redundancy as proposed in guideline OE.3 “Plan redundancies.“

Figure 4-21 Product example for over-engineering: fridge door handle

4.4 Application of the Design for Flexibility Guidelines

Altogether 34 new guidelines were collected or derived from existing approaches, which are useful for developing products in changing environments. The guidelines were clustered in six categories. All guidelines include two illustrations; one showing a favorable application of the guideline and the other one a less favorable, less flexible (less robust respectively) application. In contrast to the classical guideline format additional text has been added explaining the idea and aim of the guideline. All guidelines are collected in an A5 size booklet[11] (guidelines in Table A2 - 1 to

[11] The guidelines in the appendix are a translation of the original German version, which was initially generated and which was used for the evaluation (see Section 5).

Table A2 - 7), which can be used for learning as well as a reminder and stimulation during the development process. A short introduction to each group of guidelines is given in order to create an awareness of the basic idea as well as to optimize the understanding and support memorizing.

The booklet allows a product developer to rapidly access information. The speed of access, although not ideal, is much faster than conventional manual methods of information retrieval and because of this the application of the guidelines tends to have less of an effect, or interruption, of the thought process. Also, because the information is presented in short form, it can be read quickly and the selection process can be repeated, thereby compounding the advantage (Edwards et al. 1993).

The set of guidelines stimulates the thought process. It can be used to confirm existing solutions, refresh memory and suggest and inspire new or alternative ideas. Moreover, it can be used as a checklist. All this creates a mindset of flexibility and robust design to handle changing environments. An awareness of the importance of flexibility and robustness is generated; furthermore the guidelines can easily be used for teaching.

As mentioned before, the product developers have to keep in mind the trade-offs. They are not specifically mentioned in the booklet, because they are too much related to the context of the product, its environment and the specific development process. The guidelines should not be used excessively, and only be applied, where their application is likely to compensate changes in the product environment, negative effects caused by the changes, or where uncertainty (about requirements or future conditions related to the product) is high and thus constricts project progress. The application of the guidelines has to be based on the experience of the developers, on their “constructive Gefühl” (Reuleaux 1861), their “Feel for Design” (Hubka 1975), and on common sense. Moreover retrospective analysis of guideline application and the effects on the product and on the process can be used to enhance the knowledge of developing with help of guidelines and trigger learning effects.

4.5 Summary and Discussion

In this chapter 6 clusters with 34 new guidelines for developing flexible and robust products are presented. These guidelines are proposed as a support for developing products for changing environments. This support is for all people taking part in the product development process, especially the individual product developer. It is to give the product developer help and advice in fuzzy, uncertain situations during the process.

The set of guidelines is based on collecting existing guidelines from various approaches as well as deriving new ones from analyzing the basic ideas and principles behind product development approaches, which support the development of either flexible or robust products in one of their manifold appearances. In order to enhance understanding and memorizing the guidelines are illustrated with two pictures each, applying the basic principles from instructional design theory. One picture shows a negative example; a less flexible solution. The other picture illustrates a favorable application of the guideline, so that product flexibility or robustness is improved. One single sentence is used for every guideline to give the guidance and advice to the user. A brief text of about 50 to 100 words explains each guideline and the underlying idea. For a better overview and to ease memorizing the guidelines they are clustered in the following six categories:

- Decoupling and Modularization (MD)
- Inherent flexibility (IF)
- Easy (dis-)assembly (DA)
- Standardization (ST)
- Extended use (EU)
- Over-engineering (OE).

The new collection of design guidelines forms a handy support. It can be applied during the whole process; some guidelines are to be taken into account during product planning, while others mainly support the developer during embodiment design. Using the guidelines shall create an awareness of the problem of changing and unknown requirements. Moreover a new mindset of flexibility shall be generated. This way a new thinking of flexibility is established. The product developers are better prepared for upcoming changes.

The guideline collection does not address the trade-offs. They are too complex to be captured and handled on a generic level. They have to be taken into account and balanced by the product developer and the other people involved in the development process. This new collection is a consolidation of various approaches; it is not completely free of contradictions. Again, decisions about guideline application have to be made specifically considering the individual context of the development project.

The new set of design guidelines is derived from positive industrial case studies and scientific research; they are promising for development projects in changing environments. An evaluation of the tool is presented in the following two chapters. In Chapter 5 the evaluation method is introduced and in Chapter 6 the results will be presented.

5 EVALUATION METHOD

In Chapter 4 a new support is presented that can be applied during the product development process. It is used to stimulate the thought process, confirm existing solutions, refresh the memory, and to suggest new or alternative solutions. The whole set of 34 guidelines is based on existing and proven approaches. The single solutions have shown positive results when applied. The new consolidation, in contrast, still has to be evaluated. This is done with a laboratory study[12] with engineering design Master students. In this chapter the study design and the procedure is explained. The results are presented in Chapter 6. Before the study design is explained in detail the research questions and hypotheses concerning the new design guidelines are presented in Section 5.1.

5.1 Research Questions and Hypotheses

In the introduction (see Section 1.2.2) the three key questions of this work are introduced. Based on these questions more precise research questions are formulated and hypotheses are derived. The first key question focuses on generating a general understanding of the research topic. It can be considered the main question of Descriptive Study I of the Design Research Methodology used (DRM; Figure 1-3):

K1: What makes products suitable for changing environments?

This question is answered by means of a literature study. The answer is given in Chapter 2; either flexibility or robustness can help to handle changing environments.

The second key question is about improvement of the current situation. It focuses on support of the development process:

K2: How to develop flexible and robust products for changing environments?

The answer is given in Chapters 3 and 4. The first part of the answer leans on a literature study, while the second part of the answer, the support presented in the fourth chapter, is based on assumptions, experiences and synthesis. These are the typical means of the Prescriptive Study I of

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[12] The term *study* is used to describe the whole evaluation method. In contrast *test* is used only for the three hour period the participants are working on the design task (see 5.2 ff.)

the DRM (Figure 1-3). The answer proposed to the question of new support for the development process in changing environments is the set of 34 illustrated design guidelines that are presented above (see Chapter 4).

The third key question is part of the Descriptive Study II (Figure 1-3). It is a request for validation and evaluation of the support presented in the Prescriptive Study:

K3: Is the approach of developing flexible and robust products useful for handling changes in the environment, uncertainty and changes during the development process?

The answer of this question is based on analysis of empirical data. The data is generated and collected in the laboratory study.

In order to better handle the complex key questions K2 and K3 more precise research questions are derived and hypotheses are formulated. The answer given to the second key question K2 is only a proposition. Its validity is yet to be proven in the laboratory study that is explained below. Therefore a more precise research question and a hypothesis are formulated that have to be answered, validated respectively:

RQ1: Does the application of the proposed guideline set lead to more flexible and robust products?

H1.1: Applying the design guidelines leads to more flexible and more robust products.

The third key question is to be answered with the laboratory study as well. Two research questions and nine hypotheses are derived:

RQ2: Does flexible and robust product design, which is achieved by the application of the design guidelines, lead to better handling of changes during the development process?

Six hypotheses underlie research question RQ2. Three of these (H2.1 – H2.3) are focusing on the changes and on the process itself. The other three hypotheses (H2.4 – H2.6) are people oriented. They deal with the product developers applying the guidelines:

H2.1: When the design guidelines are used, changes can be implemented sooner after occurrence.

H2.2: When the design guidelines are used, changes can be implemented faster.

H2.3: When the design guidelines are used, implementing the changes has fewer negative effects on the design.

H2.4: When working with design guidelines, the motivation declines less when changes occur than when working without the guidelines.

H2.5: When working with the design guidelines, the stress is lower when changes occur than when working without the guidelines.

H2.6 When working with the design guidelines the contentment with the own work is higher than when working without the guidelines.

The third research question is also derived from the last key question. It aims at validation of the presented support. The third hypothesis is added in order to validate the applicability of the design guidelines in the earlier design phases, which is the main application phase of design guidelines:

RQ3: Is the developed support suitable for developing flexible and robust products?

Three hypotheses are behind this question. These are formulated as follows:

H3.1: The newly generated design guidelines are easy to understand.

H3.2: Applying the newly generated design guidelines supports the product developer when developing products in changing environments.

H3.3: The newly generated design guidelines can be applied in earlier as well as in later phases of the development process.

Applying the design guidelines and implementing flexibility and robustness in the product has its trade-offs (see Section 2.4.6). In most cases, it is not useful to compromise on quality. Therefore a good support should not have a negative effect on either quality of the concept or of the design. This is formulated in the following two hypotheses, which can be interpreted as the fundamental conditions of the guideline application:

H0.1: Applying the newly generated design guidelines does not negatively affect the quality of the concept.

H0.2: Applying the newly generated design guidelines does not negatively affect the quality of the design.

5.2 Study Design

In order to answer the research questions formulated in Section 5.1 a laboratory study was set up: Engineering design students had to work on a design problem. During the process, changes to the initial requirements were presented. Half of the students were taught the new design guidelines before the test and asked to apply these in the test. Progress of the design was documented during the whole test. In the following sections the study design is explained in detail. The results are presented in Chapter 6.

The figure below illustrates the systematic approach for laboratory studies proposed by Bender et al. (2001; Figure 5-1). In order to derive a prescriptive synthesis from initial descriptive hypotheses Bender et al. (2001) propose the approach, which was applied in this work.

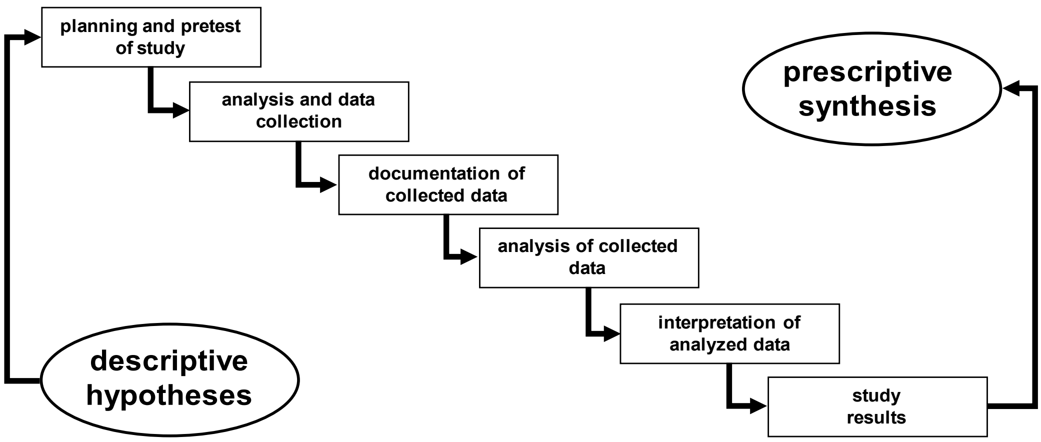

Figure 5-1 Systematic approach for laboratory studies (based on Bender et al. 2001)

According to Lienert & Raatz (1998) five quality criteria have to be taken into account in empirical research. These are objectivity, validity, empirical relevance, cost-benefit, and reliability. In this work the five quality criteria are fulfilled as follows:

Objectivity is achieved by running the study with 18 participants (see Section 5.2.6). In contrast to the subjective evaluation in the bioreactor project (see Section 2.4.4) not only the number of people applying the design guidelines is enlarged. Furthermore, the researcher is not participating in the study and the participants are not informed about the research and the goals behind the test.

Validity in this study is only based on a single test design. No different tests or methods were used in order to cross check the results. Thus, validity can only be assumed due to good preparation, execution, and interpretation of the study.

Empirical relevance is assumed, as the study is based on tools and methods, which are derived from case studies and applied science. The design task (see Section 5.2.4) and the set up (see Section 5.2.2) are realistic. Transfer of the results to practice is assumed to be possible.

Cost-benefit ratio is convenient as costs are kept low; the participants are student research teachers and student research assistants at Technische Universität Berlin (see Section 5.2.6).

Reliability concerning the evaluation of the quality of the concepts and designs produced by the participants is assured by multiple individual evaluations. Six engineering design experts[13], which were not involved in the development of the design task, evaluated the anonymized data individually (see Sections 6.1.1, 6.1.2).

5.2.1 **Variables**

Figure 5-2 illustrates the general interrelationship of variables. Below the specific variables of this study, which is set up to validate the newly derived guidelines, are explained briefly.

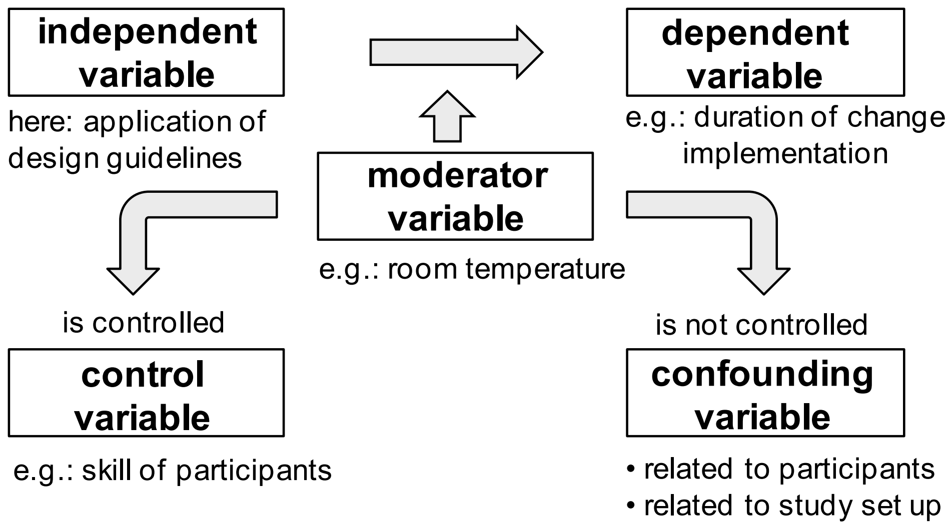

Figure 5-2 Interrelation of variable in the empirical study

The only independent variable of this study is *instruction with the design guidelines* and their recommended application. It has Boolean character as it can only be the group, which received instruction and is working with the design guidelines, or the group working without instruction and without knowledge of the guidelines. The measurement level is nominal. The two groups involved

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[13] Engineering design PhD students at Technische Universität Berlin; five of them teaching Bachelor and Master courses on engineering design; all of them are familiar with the analysis and evaluation of the Bachelor and Master exams in engineering design.

are the experimental group working with guidelines (*with GL*) and the control group working without guidelines (w/o GL).

Following dependent variables are measured for all participants. Section 5.2.3 explains how the data is collected:

- *Point of time* of change implementation for each change
- *Duration* of change implementation for each change
- *Motivation* of participants, self-assessed by the participants every 10 minutes
- *Stress* of participants, self-assessed by the participants every 10 minutes
- *Contentment* of participants, self-assessed by the participants every 10 minutes
- *Change effect*, meaning, the participants are asked what effect the single changes have on their concept and design
- *Quality of concept*, evaluated by engineering design experts
- *Quality of design,* evaluated by engineering design experts
- *Duration,* is measured
- *Completeness*, evaluated by design engineering experts.

The following data dependent variables are only collected for the experimental group working with guidelines:

- *Understanding* of the new design guidelines, participants evaluation of the comprehensibility of the guidelines
- *Support* by the new design guidelines, participants evaluation of the support given by the guidelines
- *Time of guideline application*, marking when each guideline is intentionally applied by each participant in a 20 minute resolution
- *Number of guideline applications*, marking how often each guideline is intentionally applied by each participant

The control variables, which are taken into account for this study, are:

- *Skill of participants*: based on course of study, term of study, participation in relevant courses, relevant internships, student projects, technical education, experience as student research teacher and student research assistant
- *Experience* of the participants with similar design task
- *Understanding* of design task; self-evaluation of participants after facing the design task
- *Difficulty* of design task; evaluation of participants after facing the design task
- *Interest* in design task; evaluation of participants after facing the design task.

5.2.2 Set Up

The study to evaluate the design guidelines and approve or reject the hypotheses and answer the questions is set up as illustrated in Figure 5-3. 18 student research assistants at Technische Universität Berlin attend the study. Their background, education, etc. (see Section 5.2.6) are evaluated in order to form two groups with similar skills, so that the study is not biased by different group abilities. Due to scheduling constraints the 18 participants are divided unequally into ten in the *with GL* group and eight participants for *the without GL* group. The test is run on three different days. The ten participants from the *with GL* group were taught the new guidelines in an 80 minutes lecture without exercise (see Section 5.2.5). The lecture took place the day before the test for eight participants and four days before the test for two participants (see Figure 5-9).

The participants could ask questions during the lecture. After the lecture they were given a booklet with all 34 design guidelines and asked to read it through again at home, whether they did was not verified. On the test day the participants are given a design task (see Section 5.2.4). Both groups, *with GL* and *without GL*, are given identical tasks. The participants have to work individually. The participants are read the instructions out loud before starting to ensure they all had the same level of knowledge about the procedure of the test. Questions during the test are answered only when absolutely necessary to progress. Questions, answers and time of question are collected. The task is to design a product from scratch: to generate and sketch a concept for a garden shredder. Based on this concept an embodiment design of the device has to be technically drawn with as much detail as possible.

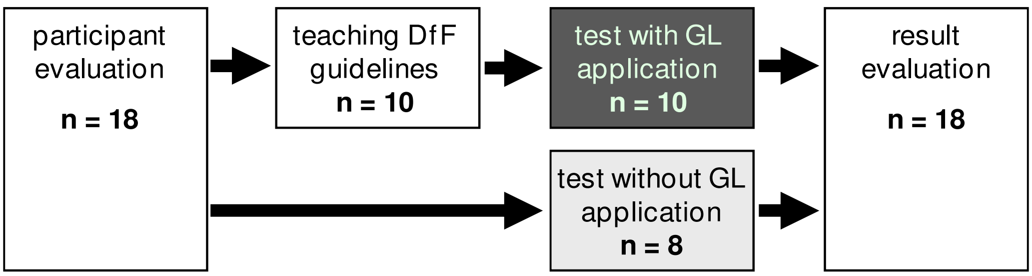

Figure 5-3 General study set up

The whole test, the concept time and design time, is limited to three hours. After one hour a 20 min coffee break is introduced; time is stopped during the break. They are told not to talk about the test in the break. It is suggested, but not compulsory, that the first hour is used to generate a concept; the two hours after the break are used for the design. The time before the break is called the concept phase, the time after the break is called the design phase.

The procedure of the whole test is illustrated in Figure 5-4. The test starts with reading introduction. Then the design task is handed out. It consisted of a requirements list and information about the electrical engine, which should be used (see Section 5.2.4 and appendix A4). Afterwards the first questionnaires are handed out (see Section 5.2.3).

The initial requirements list is handed out at the beginning of the procedure ($t=t_0$). It is supplemented and changed three times: After thirty minutes the first changes CH30.x are handed out (Table A4 - 3). After an additional 60 minutes, 90 minutes from the start, further changes CH90.x (Table A4 - 4) are handed out. Again after 30 minutes, 120 minutes from the start, the last changes CH120.x (Table A4 - 6) are handed out. This results in four phases: phase 1 before the first changes, phase 2 between first and second changes, followed by phase 3 and phase 4, which are separated by the third changes CH120.x.

If participants finished the design before the changes are handed out they are asked to wait; if the participants finished the design before the whole three hours are over, the time is recorded (neither case occurred). According to Lienert & Raatz (1998) tests can be performance tests (time is fixed and results are evaluated) or velocity tests (results have to be achieved and time is measured). The test is set up as a velocity test. Pretests suggested usability. However, the participants did not finish within the three hour time limit. Thus, results are evaluated afterwards and completeness (evaluated by six engineering design experts) taken as the measure instead of the time needed to finish the task; the test design changed into a performance test.

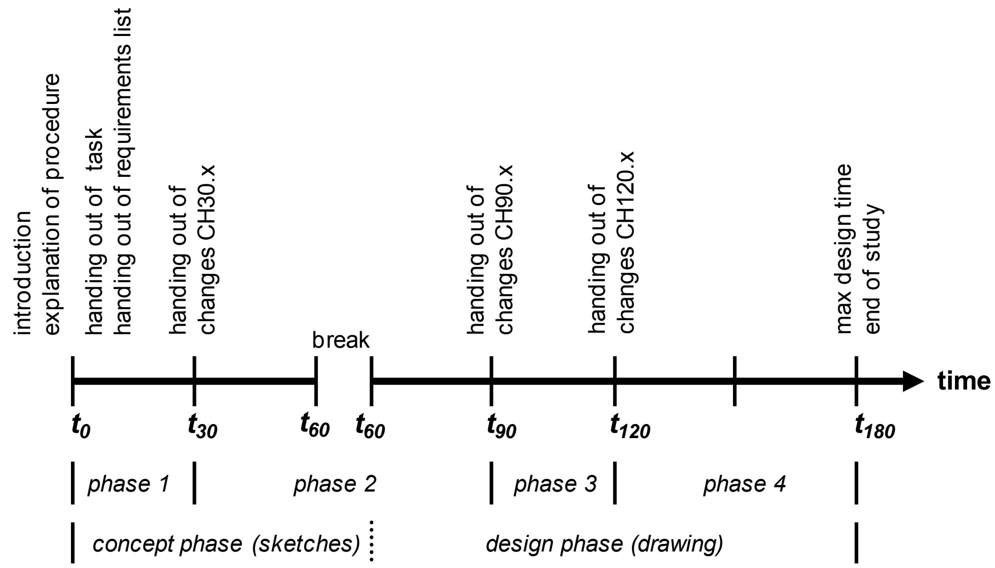

Figure 5-4 Test procedure in detail, identical for both groups

It is suggested to the participants that they develop and sketch their concepts on paper of size A4 on their table. The design should be drawn on A1 paper, using a drawing table. Figure 5-5 shows a participant working on the design at the drawing table. The *with GL* group has the design guidelines fixed on the table as a reminder and are to be marked when used for data collection (see Section 5.2.3). For both groups additional questionnaires about the changes are fixed on the table as well after handing out the changes (change questionnaires CQ1-3, see appendix A4 and Section 5.2.3). The *with GL* group is equipped with the booklet of the new design guideline.

Figure 5-5 Example of work space, identical for both groups, but guideline reminder

The two groups work in separate rooms. Each room was supervised by at least one instructed engineering designer to control, observe, and answer questions (if absolutely necessary). The individual workspaces are separated from one another, so that copying is prevented. In order to create a relaxed atmosphere, soft drinks and crackers are provided.

5.2.3 **Data collection**

In this section the different methods are described, which are used to collect the data:

Photo documentation

During the whole test (180 minutes) digital pictures were taken every 10 minutes (see Figure 5-7). The pictures are taken of every participant's sketches, calculations, drawings, and handwritten explanations. This way the progress and speed of work is documented. The photo documentation was used afterwards to check and clear out inconsistencies. Erasing (e.g. due to changes) becomes visible. The use of erasable colored pencils is obligatory.

Paper based documentation of sketches, drawings and notes

All documentation produced during the study is collected afterwards. This included A4 sheets with calculations, explanations and sketches as well as the A1 sheets with the detailed drawing. Examples are shown in Figure 5-6. In order to make progress and changes visible the color of the pen is changed every 20 minutes (see Figure 5-7).

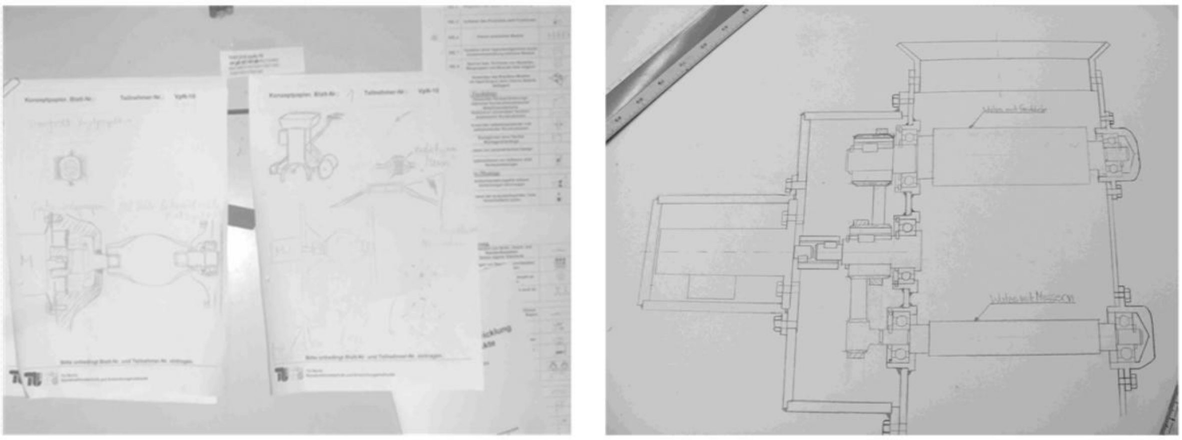

Figure 5-6 Example of concept sketch (left) at t=60 min and example of design drawing (right) at t=180 min

Questionnaires

Questionnaires are used before, during and after the test. The initial questionnaire T0 (Table A3 - 1) consists of nine questions. The first three questions about motivation, contentment and stress are repeated in all questionnaires every 10 minutes. The other questions of the first questionnaire are related to the task and asked only once. As illustrated in Figure 5-7 further questionnaires are handed out every 10 minutes (questionnaires T10 – T170, Table A3 - 2). In addition to the three questions from the first questionnaire these ask about expected overall time needed, progress and the tasks that were carried out within the last 10 minutes. The last questionnaire (T180, Table A3 - 3ff), which have to be filled after the test, had additional questions about the experiences during the test, especially the effect and handling of the changes. Questionnaire T180 also includs additional questions related to the design guidelines for the *with GL* group. The participants have to fill out these quickly and then cover them.

In addition to the questionnaires, which are presented every 10 minutes, additional questionnaires focusing on the changes are handed out together with the changes (changes questionnaire CQ1 - CQ3, Table A4 - 3, Table A4 - 4, Table A4 - 6). These questionnaires are fixed on the table so that they are visible until the end of the test. These questionnaires ask for every change that is presented (e.g. CH90.2 “easy transport with rolls”, Table A4 - 4) what effect this change has on the concept or design. Moreover it is asked at what point of time the participants start to implement and finished implementing the change. A clock is visible to all participants during the whole task.

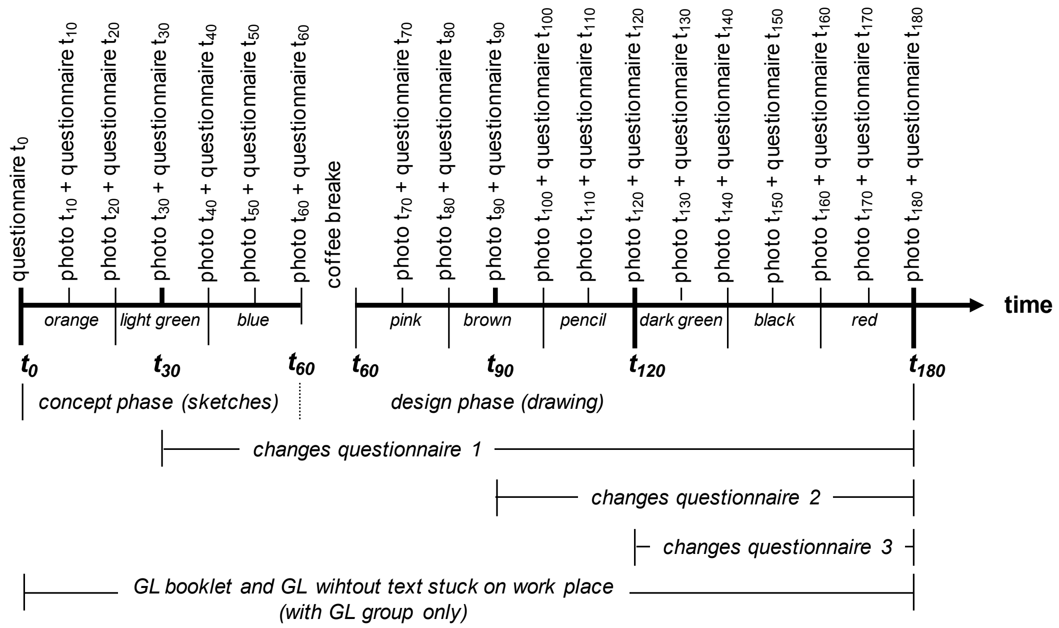

Figure 5-7 Used data collection methods in timeline

The *with GL* group has a short version of the guidelines without explanation, as shown in Figure 5-8, stuck on the table. This way the participants are reminded about applying the guidelines. Furthermore they are asked to mark with their pen every time they use a guideline intentionally. Because of the color of the pen changes every 20 minutes, the use of the guidelines during the task is documented.

Figure 5-8 shows an example of the guidelines table, which is given to the *with GL* group. The intentional use of guidelines is marked so that conclusions on the number and time of guideline applications can be drawn. The results on this are to be found in Section 6.4.3.

ME.5	Aufteilen des Produktes nach Funktionen		
ME.6	Planen autonomer Module		
ME.7	Vorsehen einer Upscalemöglichkeit durch Zusammenschaltung mehrerer Module		
ME.8	Sperren bzw. Einfrieren von Bauteilen, Baugruppen und Modulen falls möglich		
ME.9	Anwenden des Blackbox-Modells (erst Input-Output, dann interne Abläufe festlegen)		
Inhärente Flexibilität:			
IF.1	Verwenden flexibler/änderungs-toleranter Konstruktionsfeatures/ Maschinenelemente		
IF.2	Realisieren universeller/ flexibler/ anpassbarer Konstruktionen		

Figure 5-8 Example of guideline table which was on the table for the whole test period (t=0 till t=180), in addition to the guideline booklet, and marked on the right side with pen when used (*with GL* group only, showing of the original German version)

Time measurement and completeness evaluation

In addition to the photos, paper based documentation and the questionnaires, design time is supposed to be measured in order to document the velocity of working on the design task. As mentioned in Section 5.2.2 none of the participants managed to finish the task in time. Therefore time measurement was replaced afterwards by a completeness evaluation. All final drawings were presented to six engineering design experts. They are asked to evaluate the drawings and rate them on a scale of 0 (rather incomplete) to 4 (rather complete). The results are used as the completeness value, which is presented in Section 6.1.3.

5.2.4 Design Task

The design task is the development of a garden shredder. A brief description of the task, without mentioning the notation *garden shredder* is handed out to the participants. This description included ten requirements (Table A4 - 1). In addition a sheet of the geometrical data of an electrical engine is handed out (Table A4 - 2).

According to Dylla (1991) the participants should not have previous knowledge about the task. The task with the garden shredder is new to the participants. It had never been used in exercises or exams before. The complexity is at the same level as engineering design exams, which are well known to the participants. It is chosen for several reasons: There is room for creativity in the concept side as well as in the embodiment design. No specific previous knowledge is communicated in the study. It is a realistic task, which could be described with few requirements.

The requirements can be easily changed and additional requirements are possible. Pretests suggested that the whole task could be dealt with within the time limit. The finished design could be illustrated with one or few perspectives. Thus, drawing effort is limited. It is a consumer product; various solutions exist, so that comparison and evaluation of the results were eased. The garden shredder is mainly a mechanical device, which is the type of product at which the guidelines focus.

Empirical relevance of the design task is assured as it is a normal engineering design task. Thus, appearance validity is given (Bruder 2008).

The same counts for the changes. After 30 minutes three changes are presented (Table A4 - 3). Two of these are stricter versions of initial requirements (CH30.1 and CH30.2), and the other one a new function of the product (CH30.3). The five changes and additions, which are presented 90 minutes after the start, can be found in Table A4 - 4. Two are function oriented (CH90.2 and CH90.4), the other three geometry oriented (CH90.1, CH90.3 and CH90.5). As the electrical engine is to be exchanged, a new data sheet of another engine is handed out as well (Table A4 - 5). The last changes and additions are presented 120 minutes after the start (Table A4 - 6). Two functional (CH120.4 and CH120.5) and three geometrical requirements are added (CH120.1, CH120.2 and CH120.3).

All changes and additions are chosen to form a realistic example. They have an impact on the concept as well as on the design. Functional and geometrical changes are introduced. They can be implemented in various ways, mainly influenced by the participants' initial concept. Thus, they do not limit or guide creativity in a specific way. The changes and additions are chosen in a fair way; meaning they should be able to be implemented in an existing concept and design, without necessarily demanding a complete redesign every time. Moreover, the changes and additions are chosen in a way that they are not a copy of the guideline examples.

5.2.5 Training

As a training an 80 minute power point presentation is given to the ten participants of the *with GL* group. The presentation shows all 34 guidelines and the basic ideas behind these, as they are shown in Table A2 - 2 till Table A2 - 7. The difference is that the textual explanations are excluded and verbally presented. In addition to the guideline examples, the presentation gave real life examples in order to ease understanding and memorizing. It is mentioned that the guidelines aim for more flexible products in a sense to provide higher flexibility to the customers. It is not strictly demanded that the design guidelines are implemented during the test, but the participants are asked to keep them in mind and use them when this seems to make sense.

Figure 5-9 below illustrates how training and appliance of the guidelines related in time. The training was held on one day only for all ten participants of the *with GL* group. Eight of them worked on the design task with the guidelines the next day and two of them three days later. The *without GL* group did not get the training before. The eight participants from the *without GL* group attend the test on two days (three people and five people) due to scheduling reasons.

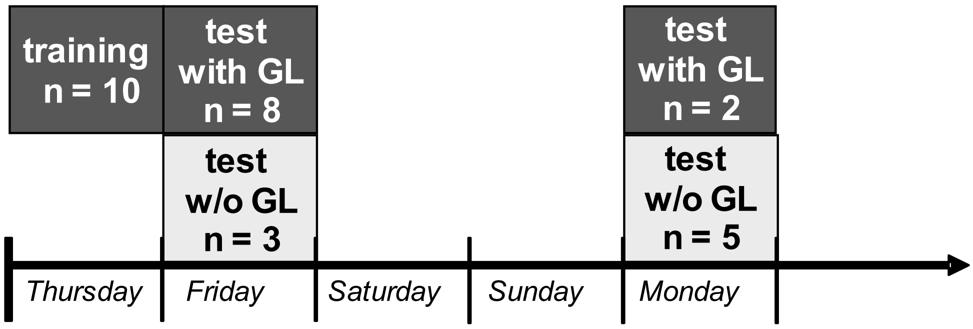

Figure 5-9 Study timeline

5.2.6 Participants

18 people participate in the study. All of them are student research assistants at Technische Universität Berlin. All are engineering students, but with different foci: Six study mechanical engineering, seven transportation engineering and five industrial engineering. Most of the courses the students have to attend are identical. The participants have studied between 5 and 13 semesters, with an average of 8.7 semesters. Their work experience as student research assistants is between 2 and 42 months; the mean is 15.2 months. One participant is female, the other 17 male. More information about the participants' background, like internships, concluded student projects, attended courses, etc. can be found in the appendix in Table A5 - 1. This data is used to calculate a *skill value* in order to form two groups of comparable skills. The skill values of the participants are shown in Figure 5-10. The figure also shows that the 18 participants were divided unequally (due to scheduling difficulties) in one group of ten participants (*with GL* group) and the group of eight participants. The mean of the skill value was somewhat higher for the *w/o GL* with 34.7 compared to 31.5 *with GL* (mean of all participants together is 32.9; for calculation see Table A5 - 1). Having slightly better skills in the *without GL* group does not bias the study in the direction of the hypotheses, but in the opposite direction. The difference, however, is not statistically significant[14]. The division of the participants is therefore considered appropriate for the study.

[14] Mann-Whitney-U-test, exact double side (no hypothesis direction) $p=0.515 > \alpha=0.05$; see 5.2.7

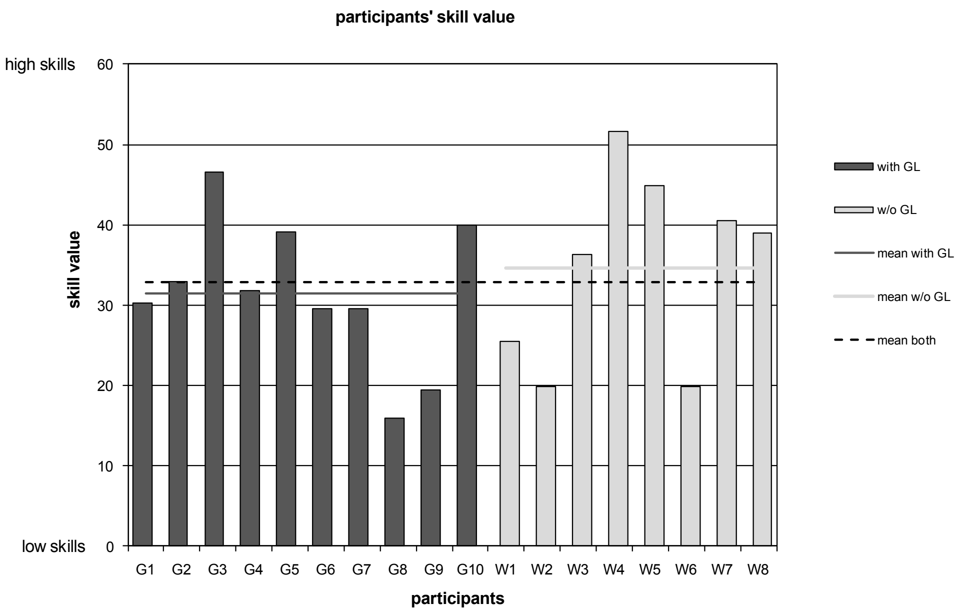

Figure 5-10 Participants' skill value

In the sense of Ahmed et al. (2003) the participants are novice product developers (or not even at that level), but among engineering students well experienced due to high involvement in teaching younger students. The newly developed design guidelines of this study aim at supporting all kind of developers. They should support the working process of less experienced as well as of more experienced developers. The particular group of students selected to participate in the study is chosen for several reasons: All students have a very similar education. Because all participants support the teaching of engineering design Bachelor courses and the correction of homework and student projects from younger students, they are familiar with engineering design tasks, which are similar to the exams. The test design task is formulated akin to the exams; duration, amount and difficulty are comparable. None of the participants has pre knowledge or study related experience with the specific task of the test.

Participation in the study was obligatory for the student research assistants, unless they had major private or university related reasons. The benefits for the students were a reduction in their working hours, practice on engineering design with a detailed feedback, and the possibility to win one of two vouchers, which were handed out based on the quality of the results (see Sections 6.1.1 and 6.1.2).

Even though the participants are not professional product developers, the conclusions of the study are relevant for industrial practice: When novice engineers are able to apply the guidelines successfully, every experienced developer should be able to do so as well. Moreover, the main idea behind this study is not to measure the absolute benefits of the guideline application, but to analyze the effects of working with the guidelines in a changing environment in comparison to working on the same task without the guidelines.

All data is anonymized. No conclusions about individual persons can be drawn.

5.2.7 **Analysis**

The data obtained from the test is analyzed with the statistical methods outlined below. More detailed information can be found for instance in (Bortz & Döring 2002, Bortz & Lienert 2007, Brosius 2008).

Several characteristics of the collected data are taken into account when choosing statistical methods for evaluation: The number of cases is small (especially as not all questionnaires were filled out correctly[15] every time); the number of cases is different in each group; normal distributions cannot be assumed.

Level of Significance

For all significance tests the confidence level is set to α=0.05. This usually provides sufficient evidence, as it means that any found difference or correlation is only statistically significant for $p \leq \alpha$ where p is the probability of obtaining the test statistic at least as extreme as the one that is actually observed, assuming that the null hypothesis is true. If two significance tests are carried out it is assumed sufficient if one test proves significance. In general, one sided significance tests are applied, as usually the hypotheses are clearly derived from theory and references, and thus formulated clearly. If the hypotheses could not be formulated clearly and directed two side significance tests to heighten evidence are used.

Statistic Tests

For the presented kind of data with small n, non-normal distributions, and nominal scales (in general) non parametrical statistical methods have to be used. For ordinal and metrical data, n>= 8, and almost same size groups the Mann-Whitney-U-Test (based on rank information) is used (Bortz & Lienert 2007). It loses validity for smaller groups and large differences in group sizes. In these cases the median test or the H-test by Kruskal and Wallis are used. The median test evens out analyzing errors in the data (e.g. caused by subjectivity) because of dichotomizing the data at the

[15] Some questionnaires were not filled out at all, some were filled obviously misunderstanding the questions asked, which was confirmed by the participants in a personal inquiry during the evaluation of the data. Thus, in this work *correctly filled questionnaires* is understood as (a) filled out and (b) as assumingly understanding the question the way it was meant to be understood.

50% level. Detailed ranking information is not taken into account (Bortz & Lienert 2007). The software used is SPSS 16 and SPSS 17 (SPSS 16 and 17).

Another statistical method used in this study is regression analysis. A simple regression analysis is used to identify the relationship between independent and dependent quantitative variables. The independent variable (or explanatory variable) is known upfront; information about the dependent variables is to be collected within the study. Here the dependent variable is the *application of guidelines*, which can either be *yes* (*with GL group*) or *no* (*without GL* group). The dependent variables are *motivation* and *contentment*.

A simple regression analysis is carried out to derive a linear equation that represents the trend of *motivation* and *contentment* over the time of the study. The regression analysis is carried out using Microsoft Excel (MS Excel 2007).

In order to check for non hypotheses related correlations, bivariate correlation tests are applied. They compute the pair wise associations for a set of variables. Usually the Spearman-ρ test and Kendall-T-b are used for ordinal scale data as these do not require ordinal values to be equidistant (interval scale) in order to deliver valid results. In this study the bivariate correlation tests are applied two sided, as no direction can be derived from theory and references. For the analysis of this study Kendall-T-b is favored over Pearson, as it is robust against extrema (Bühl & Zöfel 1999).

5.3 Summary and Discussion

Laboratory studies are not a direct representation of situations in industrial practice, but in contrast to e.g. case studies they can be set up for a very specific purpose. Here a laboratory study is used to evaluate the support, which is derived from several case studies, industrial applications, and scientific suggestions. This chapter describes the design of a study set up to evaluate the design guidelines, answer the research questions and approve or reject the hypotheses, which are derived from the key questions at the beginning of this chapter. This way, the general idea of this work can be evaluated: Already during the development of a product in a changing environment one can benefit from a flexible or robust design.

The main part of the study is a comparison of two groups of engineering design students working on the same task, while the participants of one group work in the traditional way and the participants from the other group apply the guidelines for developing flexible and robust products. The two groups are formed with similar backgrounds and abilities. The participants who had to apply the guidelines received an 80 minutes lecture on the guidelines before the test is carried out.

All participants are given the task to design, on which they have to work independently for maximum three hours. Ten requirements are given with the task. Changes and additional requirements are presented after 30, 90 and 120 minutes. Data is collected in three ways: photos of the sketches and drawings every 10 minutes, questionnaires every 10 minutes (plus before and after the test), and documentation used, all sketches, notices and drawings. The quality of the generated concepts and designs is evaluated individually by six engineering design experts. For the analysis of the data several statistical methods are used. The results are presented in the following chapter.

Even though the study is set up carefully, it has certain limitations. The number of participants is at the lower end of being sufficient for statistical analyses. The participants themselves are not from the main target group of the design guidelines, i.e. practicing engineering designers but engineering design students. The learning time is limited to less than one and half hours. The design time is only three hours instead of several weeks, months or even years. Thus, empirical relevance of the results has to be well discussed and supported by theory and literature in order to derive general conclusions for future applications.

6 RESULTS

In this chapter the results from the laboratory study described in Chapter 5 are presented. The study was set up in order to answer the three research questions and the underlying hypotheses that were derived from the initial key questions (see Section 5.1). This chapter is structured around the research questions. In addition, in Section 6.1 the results regarding the fundamental conditions (H0.1 and H0.2, see Section 5.1) are presented and discussed. Additional findings, which are not directly related to the research questions, are presented in Section 6.5. A summary and discussion of the whole evaluation concludes this chapter (see Section 6.6).

6.1 Fundamental Conditions

The following two fundamental conditions were formulated in Section 5.1 to evaluate the effect of the guideline application on the quality of the design results. This is to not trade-off the aspired benefits of flexible and robust design in a rather negative way against the quality of the design, which usually has negative effects in short and long term.

H0.1 Applying the newly generated design guidelines does not negatively affect the quality of the concept.

H0.2 Applying the newly generated design guidelines does not negatively affect the quality of the design.

The confirmation of the hypotheses is based on the analysis and evaluation of the concepts and the designs by six engineering design experts. In addition, the correlation between the quality of the results and the time of achieving these and the completeness of the designs is presented.

6.1.1 **Quality of the Concept**

Hypothesis H0.1 states that there is no quality trade-off expected when applying the guidelines in the concept phase[16]: Applying the newly generated design guidelines should not affect the quality of the concept in a negative way.

The concept sketches (A4 sheets), which the participants generated in the test, were presented to the six engineering design experts. They were made anonymous and gave no indication, as to whether the guidelines were applied or not. In order to support the evaluation process, the basic question to evaluate the quality was “does it work?” This way the evaluation was unified and focused on the concept, not on the sketching abilities. Each of the six experts had to give marks from 0 to 4 for every concept; 0 meaning low quality and 4 meaning high quality. The evaluation was carried out independently; the engineering design experts were not allowed to discuss or present their marks before the evaluation process was finished. The fulfillment of the requirements and the implementation of the changes were, besides the functionality of the main function, not explicitly analyzed. This was due to the fact that the fulfillment and the implementation could not be recognized in the concepts in a way that data for a serious evaluation could be derived.

Figure 6-1 illustrates the results for the concept quality evaluation of each participant. The bars show the mean value of the six expert evaluations. The participants from the *with GL* group are indicated as G1 to G10, the participants from the *without GL* group as W1 to W8.

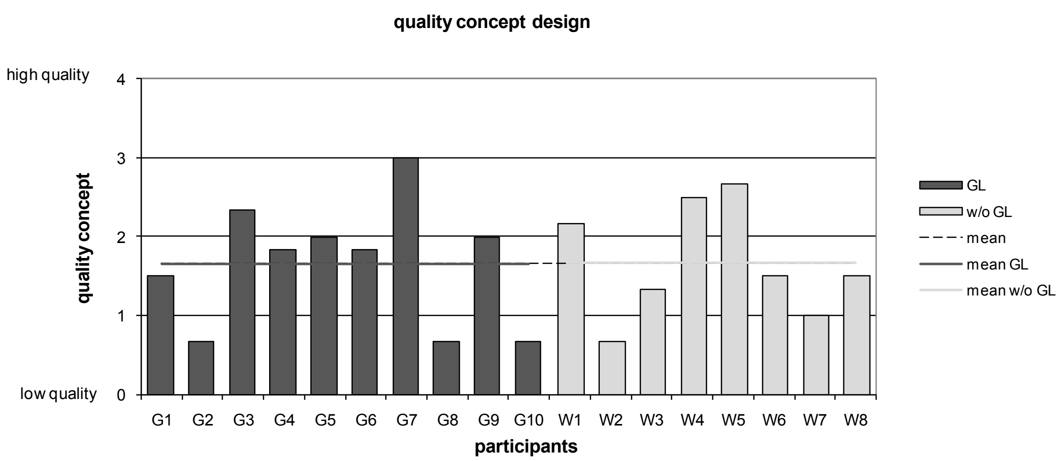

Figure 6-1 Quality concept design

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[16] Some of the participants needed more than 60 minutes for generating their concepts. However, the first 60 minutes of the test before the break are named *concept phase* and the 120 minutes after the break *embodiment design phase*.

The average mark given for the quality of the concepts from the *with GL* group is 1.65, the mean of the *without GL* group is 1.67 (overall mean is 1.66). There is no statistically significant difference in the quality whether working with or without the design guidelines (Mann-Whitney-U test, exact sig. single sided, $p=0.965$, $\alpha=0.05$)[17]. Hence, there is not enough evidence to reject hypothesis H0.1.

6.1.2 **Quality of the Design**

Hypothesis H0.2 states that there is no quality trade-off expected by applying the guidelines in the embodiment design phase: Applying the newly generated design guidelines should not affect the quality of the design results in a negative way.

The detailed design drawings (A1 sheets), which the participants generated in the test, were presented to the six engineering design experts. The drawings were anonymized and give no indication, whether the guidelines were applied or not. To support the evaluation three questions were asked:

- Does it work?
- Are auxiliary functions implemented and are constraints respected?
- How do you rate additional impressions regarding e.g. details, manufacturability, assembly, etc.?

In this way the evaluation was unified and comparability of the evaluation was increased. The evaluation was based on VDI standard 2225 (VDI 1977). Each of the six experts had to give points (from 0 to 4) for each question for each of the designs. The first question was weighted with a factor of 2; the other two questions were weighted with factor 1. The evaluation was carried out independently; the engineering design experts were not allowed to discuss or present their point before the evaluation process was finished. Again, the fulfillment of the requirements and implementation of the changes were not explicitly analyzed. This was, because the participants did not finish their designs. Analyzing whether the requirements were fulfilled and changes were implemented or not, was fuzzy. Therefore, these aspects were not explicitly used for evaluation of the quality of the designs in order to base the evaluation on more adequate data.

Figure 6-2 illustrates the results for the design quality evaluation of each participant using the mentioned weightings of 2-1-1. The bars show the mean values of all six expert evaluations. The participants from the *with GL* group are indicated as G1 to G10, the participants from the *without GL* group as W1 to W8.

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[17] H0.1 = H_0: $\mu_{GL} = \mu_{w/oGL}$
H_a: $\mu_{GL} \neq \mu_{w/oGL}$
U-test: $p > \alpha$, thus fail to reject H_0 retain 'similar quality of concepts'

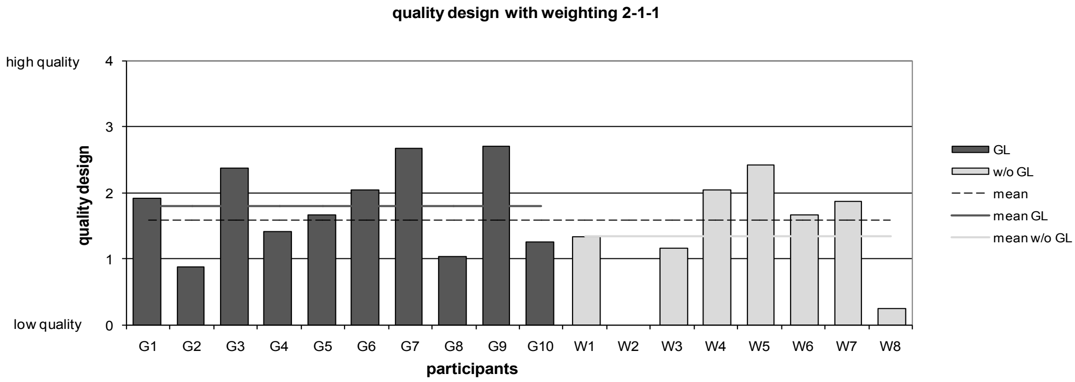

Figure 6-2 Quality design with weighting 2-1-1

The mean value given for the quality of the designs from the *with GL* group is 1.80, the mean value of the *without GL* group is 1.34 (overall mean is 1.59). The quality of the design of the *with GL* group was evaluated higher, which does not conflict with hypothesis H0.2. However, the difference is not statistically significant (Mann-Whitney-U-test, exact sig. double sided (no hypothesis direction), $p=0.360$, $\alpha=0.05$)[18]. There is no significant difference in the quality whether working with or without the design guidelines. Hence there is not enough evidence to reject hypothesis H0.2, which is therefore retained.

In addition to the three questions asked for the evaluation above, a different method to evaluate the results was used: The six engineering design experts were asked, whom of the participants they would hire if the design drawings would be the only basis for their decision. The experts were not aware, which participant used the guidelines and who worked without. All six design experts were asked to give three times two points for the most favored results and three times a single point for the fourth to sixth most favored ones. Figure 6-3 illustrates the results. The total number of points is 53 instead of 54, because one evaluator gave the single points only twice instead of three times.

[18] H0.2 = H_0: $\mu_{GL} = \mu_{w/oGL}$
H_a: $\mu_{GL} \neq \mu_{w/oGL}$
U-test: $p > \alpha$, thus fail to reject H_0 retain ‘similar quality of designs‘

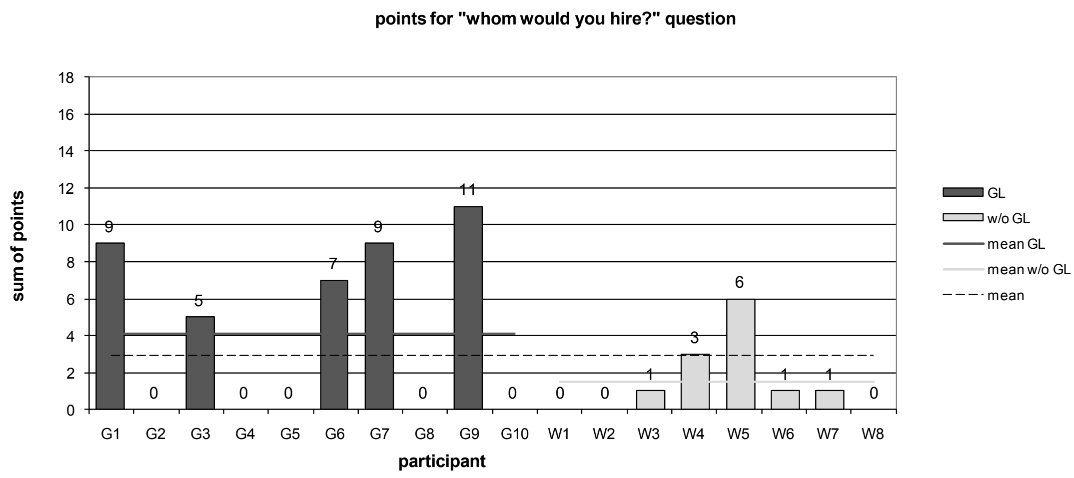

Figure 6-3 Points for "employment question"

The highest number of points that could be achieved is 12 points (2 points from each of the six experts). One participant achieved 11 points (G9), eight participants received 0 point. The mean number of points for the participants from the *with GL* group is 4.10; the participants from the *without GL* group got a mean of 1.50 points. This evaluation of the design results leads to better results for the *with GL* group (Mann-Whitney-U test, exact sig. double sided $p=0.573 > \alpha=0.05$)[19]. Thus, the difference is not statistically significant and does not interfere with the hypothesis H0.2, which therefore is retained.

6.1.3 **Completeness Quality Trade-off**

The results shown in 6.1.1 and 6.1.2 indicate that applying the new design guidelines does not have a negative effect on the quality of the concept nor on the quality of the design. In this section it is analyzed, whether the quality of the results is traded off against the needed time. Therefore data regarding time and completeness is used, which is presented in the later sections in more detail.

The completeness of the design results, which were achieved within the three hour time limit is analyzed and evaluated in Section 6.3.2. Evaluating the completeness instead of measuring the time for finishing was necessary, as none of the participants managed to finish the design task in three hours. The completeness was again described on a scale of 0 (rather incomplete) to 4 (rather complete). Figure 6-4 shows a rating diagram of the completeness of the designs on horizontal axis and the quality (see Section 6.1.2) on the vertical axis (see as well VDI 2225 (1977)). A general positive correlation of rising quality with rising completeness can be recognized – all values are

[19] H0.2 = H_0: $\mu_{GL} = \mu_{w/oGL}$
H_a: $\mu_{GL} \neq \mu_{w/oGL}$
U-test: $p > \alpha$, thus fail to reject H_0 retain 'similar quality of designs'

located near the diagonal. Thus, there was no trading off quality against completeness. This means quality does not negatively correlate with completeness, which had to be interpreted as faster work (higher completeness) leads to lower quality (quality of the design). Here the opposite can be recognized: High quality and high completeness are achieved at the same time.

However, the more complete the design is, the more precise the evaluation can be, i.e. separate assessment of both parameters is difficult. The evaluators might have been biased by this.

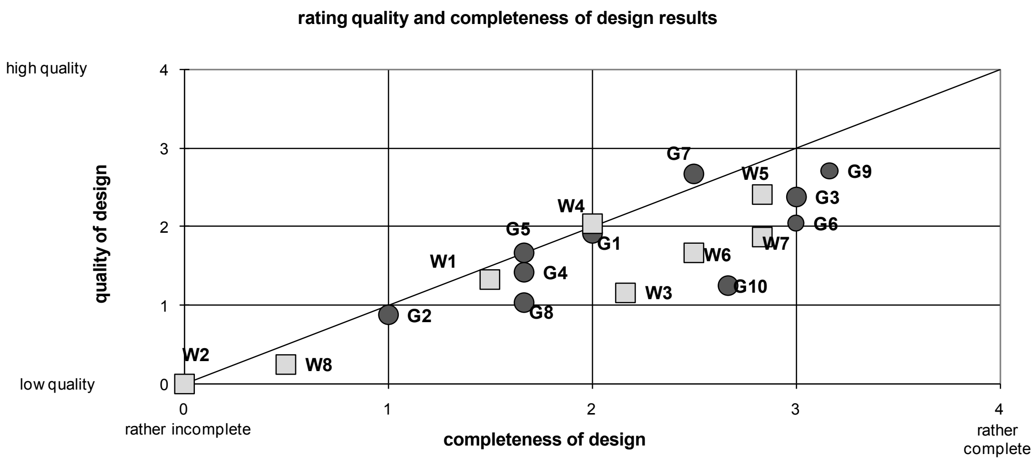

Figure 6-4 Rating diagram showing quality and completeness of design results of the participants working with the guidelines (G) and working without the guidelines (W)

An overall result evaluation value was calculated for each participant with respect to VDI standard 2225 (VDI 1977). It is the sum of completeness of the design and the quality of the design. The latter was weighted higher by a factor two. The values of the participants from both groups are shown in Figure 6-5. The mean value of the overall result of both groups was 5.23; the mean from the *with GL* group was 5.83 and the mean of overall result evaluation value of the *without GL* group was 4.48. The participants working with the guidelines performed slightly better than the ones working without the guidelines, but the difference is not statistically significant (Mann-Whitney-U test, double sided p=0.360 > α=0.05).

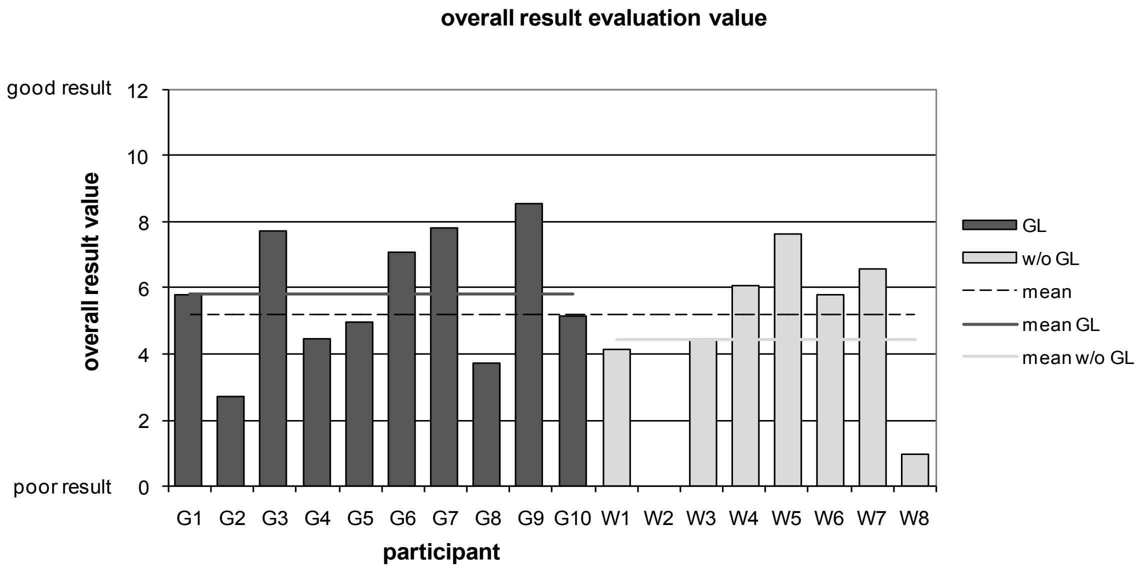

Figure 6-5 Overall result evaluation value

6.1.4 Conclusion

In summary, applying the design guidelines does neither negatively affect the quality of the generated concepts nor of the designs. Thus, H0.1 and H0.2 are retained. There is no trading-off quality of the design against its completeness. Results show the opposite trend (which is probably biased by the evaluating design experts); significant differences between the *with GL* group and the *without GL* group regarding the overall result (based on quality and completeness) cannot be found.

6.2 RQ1: Does the Application of the Guidelines Lead to More Flexible & Robust Products?

The first research question, which was formulated in Section 5.1 is:

RQ1: Does the application of the proposed guideline set lead to more flexible and robust products?

The derived hypothesis is:

H1.1: Applying the design guidelines leads to more flexible and more robust products.

In Section 2.4.5 it was explained that it is challenging, not to say impossible, to measure the flexibility of a product adequately. This is especially the case, when the product is still under development, when no customer feedback is present, and when comparisons with other products are not feasible.

6.2.1 **Initial Impact Model**

In case the success of the support proposed in the prescriptive study cannot be measured directly, Blessing & Chakrabarti (2009) propose to draw a Network of Influencing Factors. The network represents the most important statements of the research. The single statements are made of two factors that are causally linked (see Figure 6-6). The factors themselves consist of an attribute (e.g. quality or flexibility) and an element (e.g. product). Arrows are used to illustrate the causal link between two factors. A “combination of ‘+’, ‘–’ and ‘0’ signs at the ends of a link describe how the value of the attribute of the factor at one end relates to the value of the attribute of the factor at the other end” (Blessing & Chakrabarti 2009). All links are “labeled with the source(s) of the statement(s) it represents“ (Blessing & Chakrabarti 2009). These sources can be scientific references, or may also be assumptions [A], based on experience of the stakeholders [E] or based on own investigations [O].

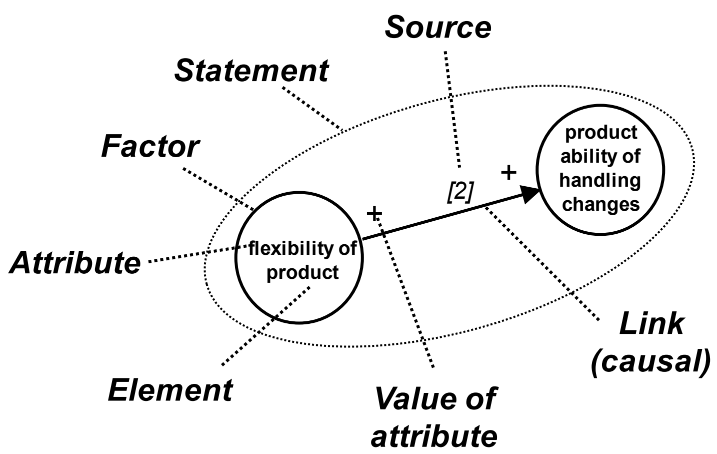

Figure 6-6 Graphical representation of a statement and associated modeling terminology (Blessing & Chakrabarti 2009)

The Network of Influencing Factors can be used for various purposes. In Figure 6-7 it is used to generate the Initial Impact Model. The Impact model illustrates an optimized situation for the product developer, as the impact of new support, which was generated throughout the research, is integrated in the model.

For one research problem various success criteria can be determined. In order to answer RQ1 other criteria are more relevant than the overall success criteria. The newly generated guidelines aim at preparing the products for better handling changes in the environment by enhancing the product flexibility or robustness. Thus, product flexibility and product robustness are the important criteria related to RQ1. They cannot be adequately measured, as no universal support is present (see Section 2.4.5). Hence, new measurable criteria had to be defined and the links between them have to well argued and supported with proven references. An excerpt of the Initial Impact Model for the application of the design guidelines, which were derived in Chapter 4, is illustrated below (Figure 6-7).

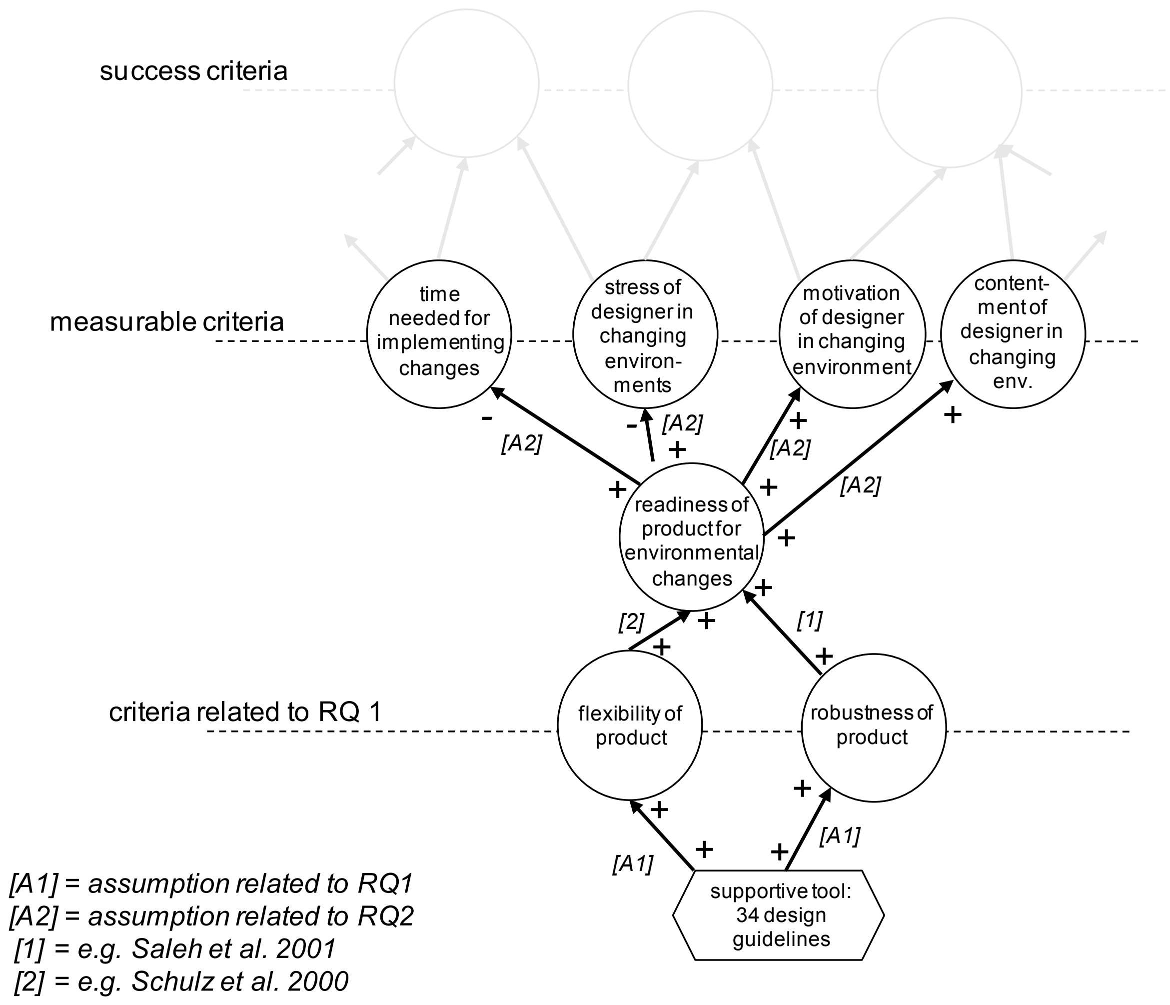

Figure 6-7 Applying the Initial Impact Model (excerpt)

The Impact Model, as illustrated above, is strongly based on assumptions, which are derived from the research questions RQ1 and RQ2. In order to evaluate the assumptions, on which hypothesis H1.1 is based, and to answer the research question RQ1 the assumptions underlying RQ2 have to be positively evaluated. The assumptions on RQ1 and the answer of the question itself can only be derived reversely in an argumentative way.

6.2.2 **Conclusion**

No suitable method is present to measure the products' flexibility and robustness. Hence, it is not possible to answer research question RQ1 directly. It can only be discussed and argued based on the findings and answers on the other research questions and hypotheses.

Based on the Initial Impact Model shown in Figure 6-7 the argumentation regarding RQ1 is as follows: If the measurable criteria, which are related to the second research question RQ2 show the assumed effects, the assumptions [A2] related to RQ2 can be considered positive. The links between the readiness of the product for environmental changes and the flexibility and robustness is well proven by various references (e.g. Saleh et al. (2001) and Schulz et al. (2000)). Hence, the assumptions [A1] related to RQ1 can be considered positive as well as there are no other causal links, which would explain the effects.

Therefore, answering the question, whether the application of the proposed guideline set leads to more flexible (and robust) products or not is left open until summary and discussion of the evaluation of this chapter in Section 6.6 and the final conclusions in Chapter 7.

6.3 RQ2: Better Handling of Changes During Development?

The second research question RQ2 is about handling the changes that occur during product development:

> RQ2: Does flexible and robust product design, which is achieved by the application of the design guidelines, lead to better handling of changes during the development process?

Six hypotheses are formulated to specify this question: Three of them (H2.1 – H2.3) focus on the changes and on the process itself (see Sections 6.3.1 - 6.3.4). The other three hypotheses (H2.4 – H2.6) deal with the developers applying the guidelines (see Sections 6.3.5 - 6.3.7).

Neither the sketched concepts nor the drawn designs could be used to analyze in a serious and comparable way the quality of the change implementation (see Sections 6.1.1, 6.1.2). Hence, for this whole section it is taken as an empirical fact that the participants worked on the change implementation, if they stated it this way. This seems feasible as the results presented below support this theory.

6.3.1 Starting Time for Change Implementation

Hypothesis was derived as follows:

H2.1: When the design guidelines are used, changes can be implemented sooner after occurrence.

Figure 6-8 illustrates the starting times of the two groups *with* and *without* the guidelines. The times are shown independently for each change (CH30.1 - CH120.5). Most questionnaires (Table A4 - 3, 4, 6) are either not filled out at all or filled out incorrectly (see Section 5.2.7). The number of correctly filled questionnaires is rather low as indicated in the figure: For the *with GL* group the number of correctly filled questionnaires is between 1 and 3 (out of 10), for the *without GL* group the number is between 0 and 2 (out of 8). Therefore no statistically valid conclusion can be drawn from this data.

The single starting times for each point of time, when changes were presented, can be summed up for each group (e.g. $\Sigma t_{30.x \text{ with GL}} = t_{30.1 \text{ with GL}} + t_{30.2 \text{ with GL}} + t_{30.3 \text{ with GL}}$). This way comparisons between the *with GL* and the *without GL* group could be carried out for each of the three groups of changes (CH30.x, CH90.x, CH120.x) despite focusing on the single changes. The horizontal lines in Figure 6-8 indicate that in average the participants of the *with GL* group started implementing the changes earlier than the participants of the *without GL* group. Nevertheless, the summed up number of useful cases is still too small for a statistical analysis.

In order to achieve a sufficiently large number of samples the starting times of all changes were summed up with no respect to the single change or the group of changes: The sample size of 28 answers for the changes of the *with GL* group and 14 answers for the changes of the *without GL* group seems sufficiently large for a statistical analysis. On average the *with GL* group started implementing the changes before the *without GL* group. The average starting time of the *with GL* group was at 93 minutes in contrast to 105 minutes of the *with GL* group. However, the difference is not statistically significant (Mann-Whitney-U test, exact sig. double sided (no hypothesis direction) $p=0.347 > \alpha=0.05$) and more importantly these samples are based on only seven participants (four participants respectively). The numbers are different to the ones under the columns in Figure 6-8, because not all participants answered each question. The data shown in Figure 6-8 was always from the same participants. Thus, the data cannot be used for a reasonable evaluation.

It is not clear, whether or not the guideline application leads to an earlier change implementation. No conclusion can be drawn for the hypothesis H2.1; it is neither rejected nor supported due to insufficient data.

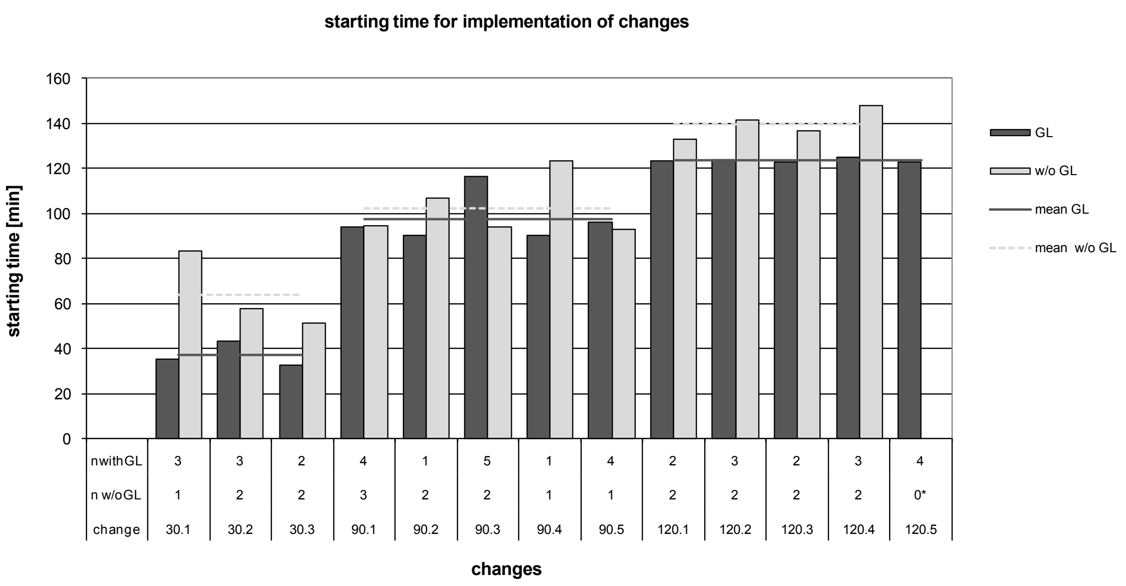

Figure 6-8 Starting time for implementation of changes

6.3.2 **Duration of Change Implementation**

The second hypothesis that was derived from the research question RQ2 is formulated in 5.1 as follows:

H2.2 When the design guidelines are used, changes can be implemented faster.

Here the hypothesis is tested for the changes in the concept phase as well as for the changes, which were presented during the embodiment design phase.

Change implementation in concept phase

Direct measurement of the duration, the time needed, for change implementation was not possible. Therefore, the duration of the whole concept phase was measured. The less the changes affect the process the faster the change implementation could be carried out and the less overall time for the concept phase is assumingly needed. The concept times of the participants were derived from the photos, which were taken every 10 minutes. The point at which the participants switched from the A4 paper of the concept phase to the A1 paper of the embodiment design phase was checked with help of the photo documentation. The ending time of the concept phase was calculated as the time of the first picture of A1 drawing minus 5 minutes as this is the mathematical average between the last photo, where the participants worked on the concept, and the first photo on which the participants worked on the embodiment design; thus it was the theoretical point of time, when the concepts were finished. Figure 6-9 illustrates the calculated times.

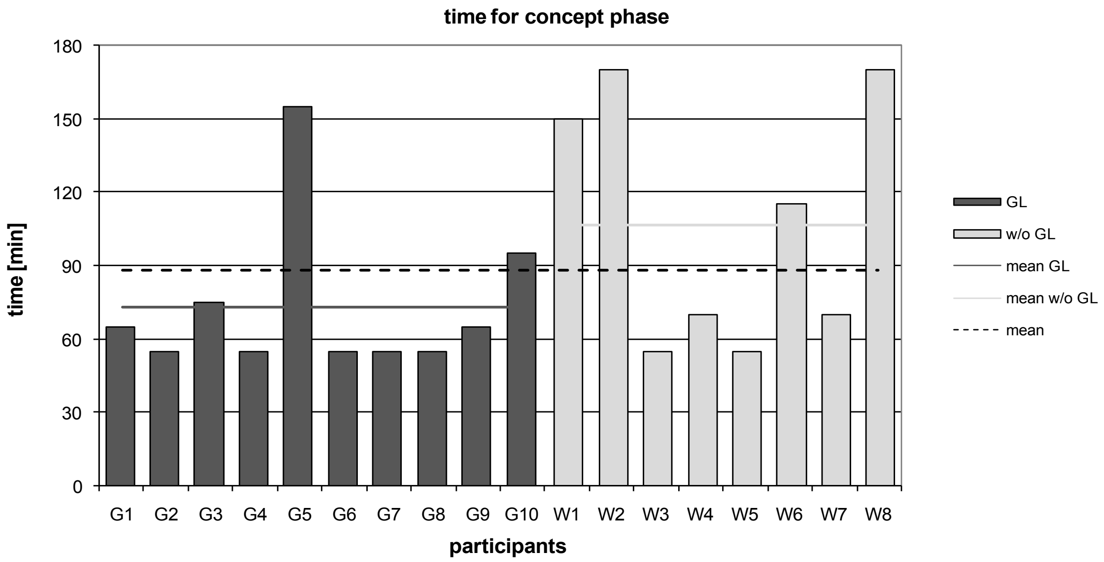

Figure 6-9 Time for concept phase

The average time for the concept phase was lower for the *with GL* group compared to the *without GL* group; 73 minutes compared to 107 minutes (Mann-Whitney-U test, exact sig. single sided (hypothesis driven) $p=0.073 > \alpha=0.05$)[20]. No statistical significance can be found in the data. The actual duration is likely to be influenced, because in the beginning of the test the participants were encouraged to change from concept to embodiment design after 60 minutes and the overall time of the study was limited to 3 hours, but this was true for both groups. In conclusion, the data shown in Figure 6-9 indicate a trend for lower concept time for the *with GL* group in comparison to the *without GL* group, but no statistical significance.

Change implementation in embodiment design phase

The starting time of implementing changes, which occurred during the embodiment design phase (CH90.x and CH120.x) were measured with the questionnaires shown in Table A4 - 4 and Table A4 - 6. Only a few questionnaires were filled out correctly. Hence, the sample size is too low; the data, which are illustrated in Figure 6-8, cannot be analyzed with statistically thoroughness.

Therefore instead of measuring and analyzing the time needed for implementing the individual changes the overall completeness of the embodiment design was used for analysis. The less the changes affect the process the faster the changes can be implemented and the less overall time for the embodiment design was needed; the final results were more complete after 3 hours, respectively. As mentioned in Sections 5.2.2 and 5.2.3 none of the participants finished the design

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[20] H_0: $\mu_{GL} = \mu_{w/oGL}$
H2.2 = H_a: $\mu_{GL} \neq \mu_{w/oGL}$
U-test: $p > \alpha$, thus fail to reject H_0, reject ‘faster implementation with GL‘

task within the three hour time limit. Therefore, instead of measuring the overall time, the completeness of the designs after three hours was evaluated. The completeness was assessed by six engineering design experts. They separately evaluated the final drawings of each participant and rated each drawing from 0 for rather incomplete designs to 4 for rather complete designs. The evaluation process was supported by the question "how complete is the design?" The mean values of these evaluations are shown in Figure 6-10. The overall mean value of completeness is 2.04 points; the mean completeness of the *with GL* group is 2.23 which is higher than the score of the *without GL* group of 1.79 points. However, the difference is not statistically significant (Mann-Whitney-U test, exact sig. single sided (hypothesis driven) $p=0.204 > \alpha=0.05$)[21].

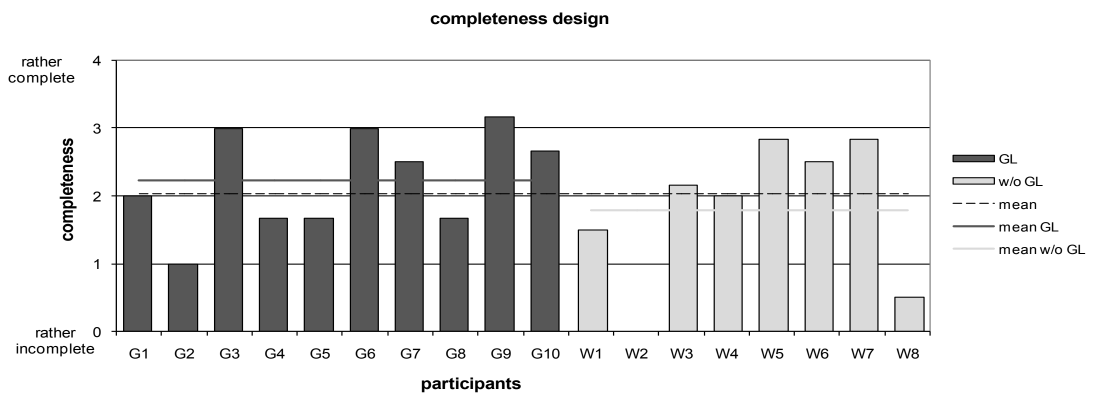

Figure 6-10 Completeness of design

Figure 6-9 and Figure 6-10 indicate that the *with GL* group finished their concepts faster as well as they created more complete designs. However, the statistical analyses show that the analyzed effects are not statistically significant. Thus, no general conclusion can be drawn, whether the application of the guidelines leads to faster change implementation or not. Based on the actual data H2.2 (When the design guidelines are used, changes can be implemented faster.) has to be rejected. Further research with a higher number of participants or another test design with more precise measurement methods for the change implementation is recommended (see as well Section 7.3).

6.3.3 Workload of Change Implementation

Even though the evaluation of hypothesis H2.2 (When the design guidelines are used, changes can be implemented faster.) in Section 6.3.2 did not lead to the expected results here the same hypothesis is evaluated from another perspective.

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[21] H_0: $\mu_{GL} = \mu_{w/oGL}$
H2.2 = H_a: $\mu_{GL} \neq \mu_{w/oGL}$
U-test: $p > \alpha$, thus fail to reject H_0, reject 'faster implementation with GL'

Measuring time and evaluating completeness does not lead to a definite evaluation of H2.2. Therefore the answers to the starting and finishing times of changes implementation in the change questionnaires CQ1 – CQ3[22] were evaluated (Table A4 - 3, Table A4 - 4, Table A4 - 6). Furthermore the answers to one question of the questionnaires T10 to T180 (Table A3 - 2, Table A3 - 3) were evaluated. This question[23] was: "What task have you been working on within the last 10 minutes?"

Figure 6-11 illustrates the duration needed to implement the changes. The data was collected with the questionnaires CQ1 – CQ3. More than one change could be implemented at a time. The mean duration of the *with GL* group is 21.0 minutes. The mean duration of the *without GL* group was almost identical at 21.1 minutes. Besides not showing a difference between the two groups the data is again based on very few samples, as not all questionnaires were filled out correctly. Thus, statistical analyses were not performed.

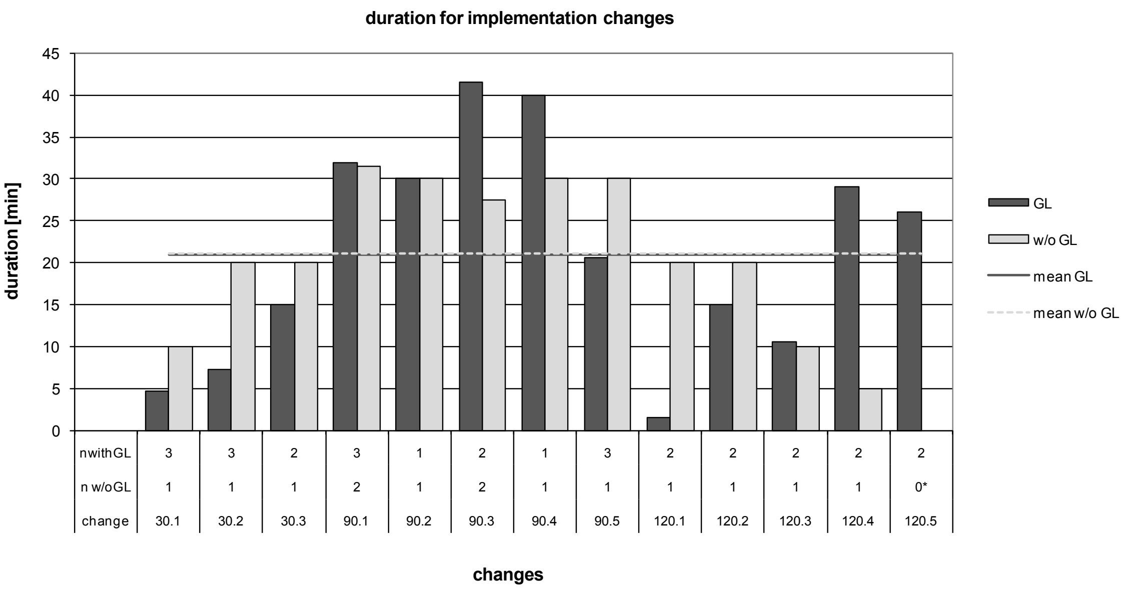

Figure 6-11 Duration for implementation changes

In questionnaires T10 to T180, which were handed out every 10 minutes, the participants were asked, on which of 15 possible tasks they worked *not all*, *somewhat* and/or *intensively* (see Table A3 - 2, Table A3 - 3). One of the tasks was "implementing changes". For the evaluation marking *intensively* was rated with two points, working *somewhat* on a task was rated one point and *not at all* is calculated zero points. The questionnaires, in which the participants got a total of more than

[22] These questionnaires asked for starting and finishing time for every single change so that the duration of the change implementation for every single change could easily be calculated.

[23] It is question number six on questionnaires T10 and T20; question number seven on the questionnaires T30-T180. The number of the question changed, as after the first changes a new question was added.

10 points, were excluded from further evaluation (excluded: G1, G4, G10, W5). These were considered as filled out incorrectly, as it is not possible to work on too many tasks at the same time. Personal inquiries after the study revealed the misunderstanding of the question (see Footnote 23 on page 141); the participants understood the question as “What tasks have you been working on till now?” instead of “…within the last 10 minutes?”

To evaluate the hypothesis the mean points given for the task “implementing changes” for both groups together and individually were compared. The calculated mean values for every 10 minutes are shown in Figure 6-12. The higher the value the more often the participants were *somewhat* or *intensively* working on the task “implementing changes”.

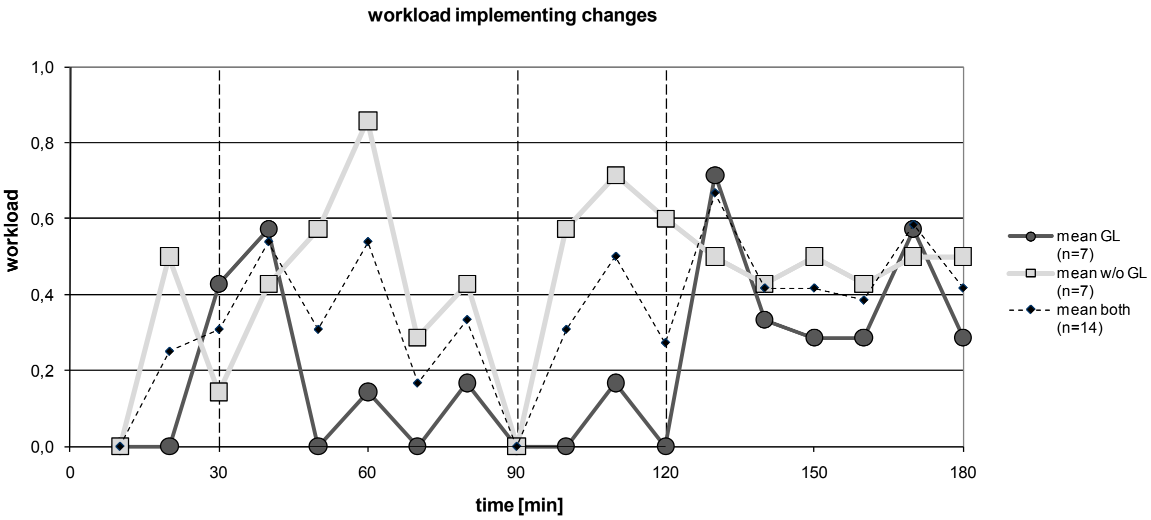

Figure 6-12 Workload implementing changes

Interestingly some participants were already implementing changes, before the new changes and additions (Table A4 - 3) were presented to them. Strong increasing of workload of implementing changes can be observed shortly after the changes were presented at 30, 90 and 120 minutes after the start. As can be derived from Figure 6-12 especially the first two changes CH30.x and CH90.x affected the *without GL* group, while the later ones CH120.x had more impact on the *with GL* group.

According to H2.2, changes should be implemented faster when using the guidelines; thus, the mean workload of the *with GL* group would be expected to be lower. Using Mann-Whitney-U test to prove the assumed lower workload of the *with GL* group for each point of time, leads to somewhat less clear results: Huge differences in the workload in implementing the changes can be identified in Figure 6-12. The figure indicates that the workload of implementing changes was lower for the *with GL* group than the workload of the *without GL* group. However, the Mann-

Whitney-U-test[24] (exact significance single sided) shows that the differences for none of moments, when the data were collected, are statistically significant, even though the differences seem to be rather large, especially for t=50, 60, 100, 110 and 120. Nor the difference in overall workload summed up over the whole study is statistically significant. Following this evaluation H2.2 has to be rejected.

If the questionnaires from the participants, who marked “implementing changes” not even a single time during the whole study (but marked other possible answers on this question), are excluded from the analysis, the results slightly change: The difference in workload on “implementing changes” can be considered statistically significant for t=60 minutes and the overall workload (Mann-Whitney-U test, exact significance, single sided, $p_{t60*}=0.024 < \alpha=0.05$; $p_{whole*}=0.037 < \alpha=0.05$).

In summary the values illustrated in Figure 6-12 point in the direction of the hypothesis that changes can be implemented faster, when the design guidelines are used (H2.2); as less time is spent on implementing the changes. The statistical analysis, however, supports this hypothesis for a single point in time (t=60) and for the overall workload for implementing changes. Nevertheless, H2.2 cannot generally be supported, thus has to be rejected.

6.3.4 **Effect of Changes**

Hypothesis H2.3 states: When the design guidelines are used, implementing the changes has fewer negative effects on the design. Data to evaluate this hypothesis were collected with the change questionnaires. These were handed out with the changes and additions and stayed with the participants until the end of the test, so that they could be filled out at any time (Table A4 - 3, Table A4 - 4, Table A4 - 6). For every change and addition, which was presented during the study, the participants were asked what effect the particular change or addition had on the participants' concept or design, which they had generated so far. The participants could mark *no effect at all*, *partly redesign* or *complete refusal*. The answers are illustrated in Figure 6-13.

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[24] H_0: $\mu_{GL} = \mu_{w/oGL}$
H2.2 = H_a: $\mu_{GL} \neq \mu_{w/oGL}$
U-test: $p > \alpha$, thus fail to reject H_0, reject ‘faster implementation with GL‘ (tested for all points in time t)

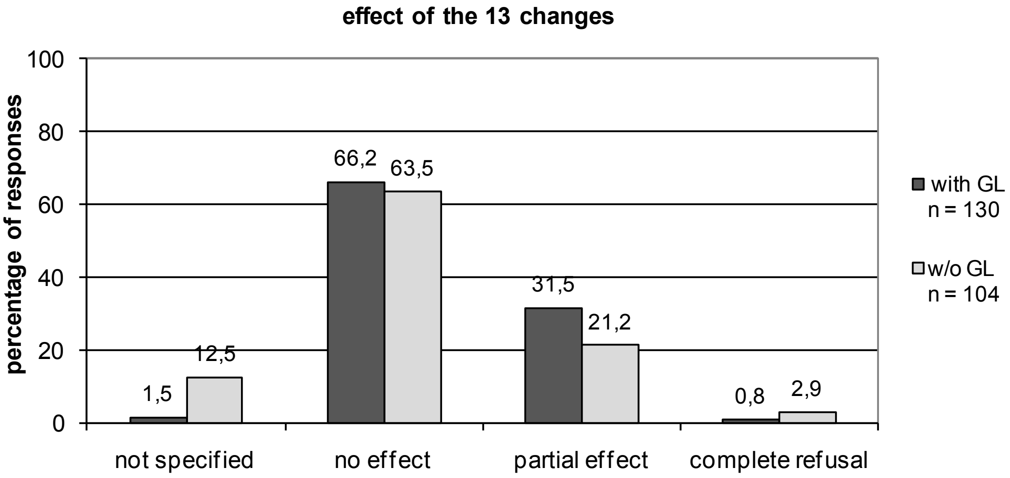

Figure 6-13 Effect of the changes on the concepts and designs

Both groups most often stated that the presented changes had *no effect* on their concepts and designs. The *with GL* group reported 41 times that the changes and additions *partly* had an effect on the concepts and designs. 19 times the participants of the *without GL* group reported a *partial* effect of the changes and additions on their concepts and designs[25]. One time a change caused a complete refusal of the current design for one participant of the *with GL* group and three times for the *without GL* group. In all cases it concerned CH90.3, the adjustable size of the shredding good, which caused the participants to start over their design process.

If hypothesis H2.3 is true, less negative effects would be expected for the *with GL* group. This means fewer effects at all (more mentions on *no effect* respectively) and less *complete refusal*[26]. The numbers shown in the Figure 6-13 and statistical analyses do not support this hypothesis: The higher percentage of responses on *no effect* of 66.2 for the *with GL* group compared to 63.5 of the the *without GL* group is not statistically significant[27] (Mann-Whitney-U test, exact sig. single sided (hypothesis driven) $p_{\text{no effect}}=0.287 > \alpha=0.05$). Less responses on *complete refusal* for the *with GL* group would support hypothesis H2.3, but due to the low number of responses no statistically significant evaluation can be made here.

[25] Group sizes are different; $n_{withGL} = 10$, $n_{w/oGL} = 8$; each participant was asked once for each of the 13 changes; thus there are 130 answers for the *with GL* group and 104 for the *without GL* group.

[26] No evaluation can be made regarding *partial effect*, as this is worse than *no effect*, but a definitive benefit over *complete refusal*.

[27] H_0: $\mu_{effectGL} = \mu_{effectw/oGL}$
H2.3 = H_a: $\mu_{effectGL} \neq \mu_{effectw/oGL}$
U-test: $p > \alpha$, thus fail to reject H_0, reject ‘less negative effect when working with GL‘

In addition and not related to the hypothesis, the following analyses were carried out in order to see, if there is a difference in the effect on the current concept and design between strictly geometrical and functional changes and additions. Overall 13 changes and additions were presented to the participants during the test. The changes CH30.1, 90.1, 90.5, 120.1, 120.2, and 120.3 can be understood as geometrical changes and additions. The other seven changes and additions were function related.

Functional changes were mentioned more often as having *no effect* on the current concept and design, than the geometrical changes: 60.0 % for geometrical changes compared to 68.9 % for functional ones (see Figure 6-14). In contrast, functional changes were responded less often to have a *partial* effect on the concept and design, but they led to complete refusal (CH90.3). This did not happen for the geometrical changes. Due to the small sample sizes these differences in the effect of geometrical and functional changes are not statistically significant; (Mann-Whitney-U test, exact sig. double sided, (no hypothesis) $p_{\text{no effect}}=0.445 > \alpha=0.05$; $p_{\text{partial effect}}=0.295 > \alpha=0.05$; $p_{\text{complete refusal}} = 0.731 > \alpha=0.05$)[28].

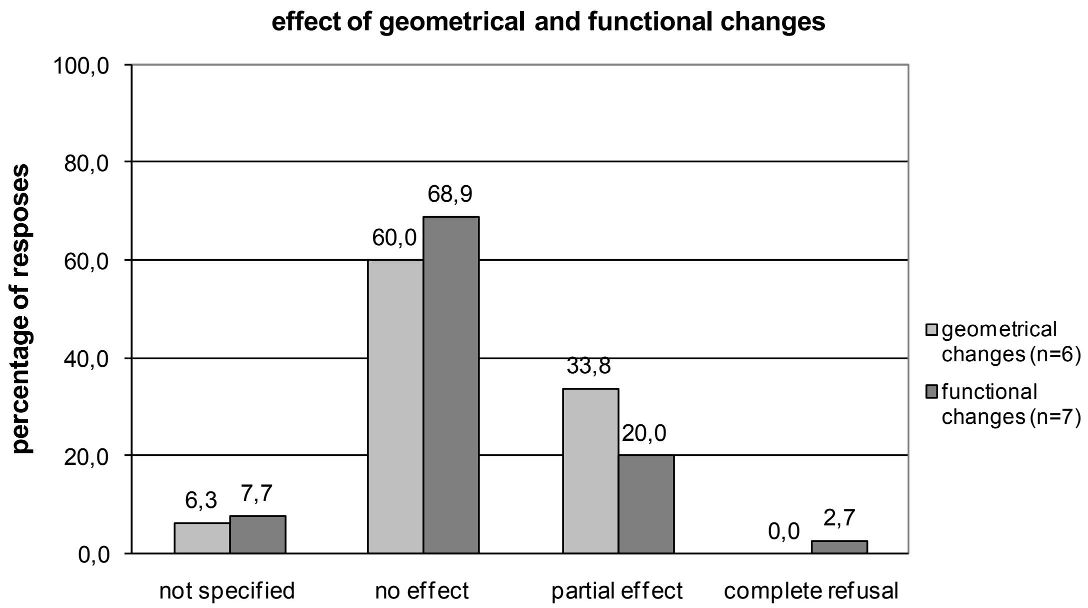

Figure 6-14 Effect of geometrical and functional changes

In summary, even though differences in the effect of changes between the *with GL* group and the *without GL* group can be found that point in direction of hypothesis H2.3 the differences are not statistically significant. Therefore, the hypothesis has to be rejected. Only one functional change

[28] H_0: $\mu_{\text{functional}} = \mu_{\text{geometrical}}$
H_a: $\mu_{\text{functional}} \neq \mu_{\text{geometrical}}$
U-test: $p > \alpha$, fail to reject H_0 conclude ‘no differences between funcitonal and geometrical changes‘

(addition CH90.3) led to complete refusal of the current concept or design. Again, no statistical significant difference was found between geometrical and functional changes.

6.3.5 Motivation

One of the motivations for the guideline application was that due to eased incorporation of the changes the participants' motivation of the *with GL* group is higher or declines less when changes are presented compared to the *without GL* group. Therefore hypothesis H2.4 was formulated as: When working with design guidelines, the motivation declines less when changes occur than when working without the guidelines. In order to evaluate this hypothesis all participants were asked about their current motivation every 10 minutes during the test (Questionnaires T0 – T180, see Table A3 - 1, Table A3 - 2, Table A3 - 3ff). The participants could rate their personal motivation in six steps from *not motivated* to *extremely motivated*. In order to not bias an evaluation with the previous one, the participants were asked to cover the questionnaires after filling out. Figure 6-15 illustrates the progression of the participants of the *with GL* group and the *without GL* group. Regression analyses show an almost identical decline in motivation for both groups during the test. One major difference is that the *with GL* group had an overall higher motivation, which is statistically significant.

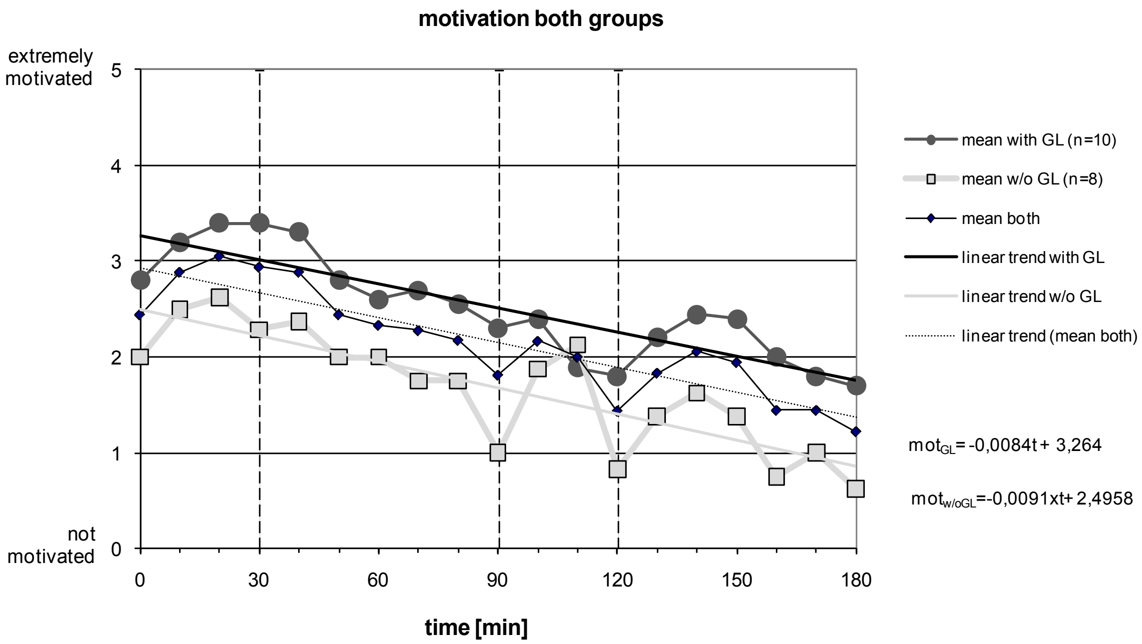

Figure 6-15 Progression of motivation for both groups

For the comparison of motivation between the two groups for each point of measurement (every 10 minutes) the Mann-Whitney-U test is applied. In Table 6-1 and Table 6-2 the results of the analyses are presented.

The level of significance is set to α=0.05. With these values statistically significant differences between the *with* and the *without GL* group can be found, when the changes are presented at t=30 (t=40) and t=90 minutes[29] as it can be easily recognized in Figure 6-15. Applying the new design guidelines had a positive effect on the motivation directly when changes occurred (even though not statistically significant at t=120); that analysis also shows that there is a general positive effect on motivation for the *with GL* group, which is statistically significant[30].

Table 6-1 Differences in motivation from t=0 to t=90

	mot t0	mot t10	mot t20	mot t30	mot t40	mot t50	mot t60	mot t70	mot t80	mot t90
Mann-Whitney-U	23	27.5	29	17.5*	21*	26	29.5	24.5	22	11*
exact sig. (1-tailed sig.)	.073	.137	.180	.044	.051	.119	.180	.087	.100	.021

*. significant on level α = 0.05 (1-tailed sig.)

Table 6-2 Differences in motivation from t=100 to t=180, and motivation during whole test

	mot t100	mot t110	mot t120	mot t130	mot t140	mot t150	mot t160	mot t170	mot t180	whole mot
Mann-Whitney-U	30	33.5	16	26.5	24.5	24	18*	28	21.5	9296*
exact sig. (1-tailed sig.)	.204	.408	.074	.119	.139	.087	.028	.158	.051	.000

*. significant on level α = 0.05 (1-tailed sig.)

Comparing the motivation of the two groups

While above the motivation between both groups was analyzed for every 10 minutes, the Figure 6-16 illustrates the mean motivation of the participants from both groups related to the phases. The phases were defined by the changes and additions, which were presented at 30, 90 and 120 minutes. Thus, 1st phase is 0 – 30 minutes, 2nd phase is 30 – 90 minutes, 3rd phase is 90 – 120 minutes and the 4th phase was from 120 to the end at 180 minutes. The motivation in each phase was based on all questionnaires (T0-T180) from all participants in each group that were filled out in each phase.

[29] Questionnaires are filled out after the changes are handed out.

[30] H_0: $\mu_{motGL} = \mu_{motw/oGL}$
H2.4 = H_a: $\mu_{motGL} \neq \mu_{motw/oGL}$
U-test:
p < α, reject H_0, retain H_a'motivation declines less when working with GL' for t=30, t=40, t=90, t=160min
p > α, fail to reject H_0, retain 'no difference in motivation'for t≠30, t≠90, t≠160min

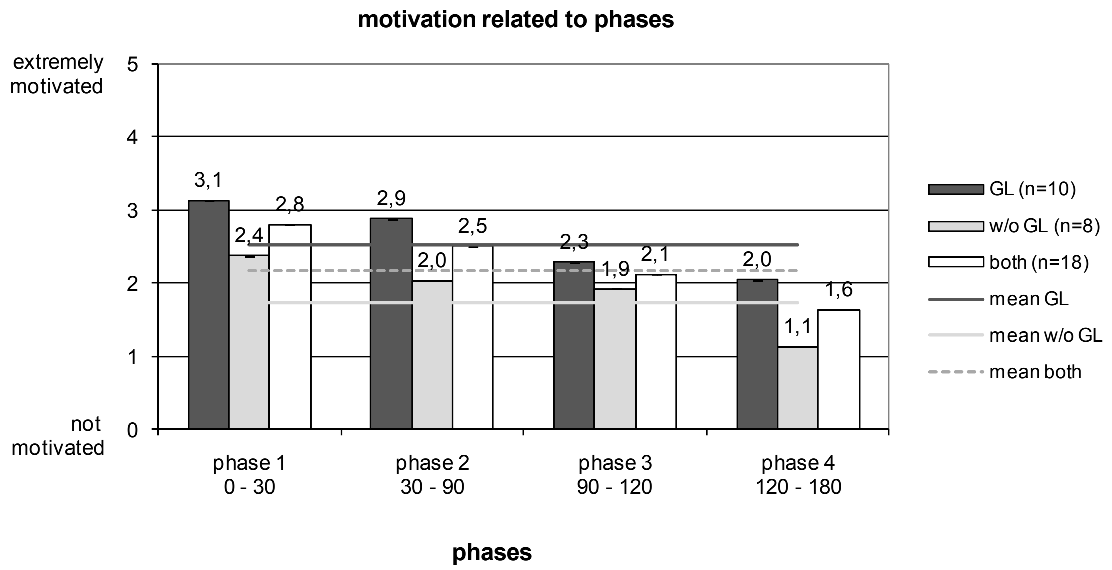

Figure 6-16 Motivation of participants related to phase defined by the changes, including contentment of both groups together

As shown already before in Figure 6-15, the motivation of the *with GL* group was higher than the motivation of the *without GL* group. In all four phases the participants of the *with GL* group rated their motivation higher than the participants of the *without GL* group (see Figure 6-16). The Table 6-3 shows the results of a comparison of the motivation per phase (Mann-Whitney-U test)[31].

Table 6-3 Differences in motivation between both groups per phase; phases defined by points in time, when changes are presented

	mot phase1	mot phase2	mot phase3	mot phase4
Mann-Whitney-U	239.5*	857.0*	238.5	1108.5*
exact sig. (1-tailed sig.)	.022	.000	.057	.000

*. significant on level α = 0.05 (1-tailed sig.)

The difference in motivation between the two groups is statistically significant in all but the 3rd phase. This means that in the 1st, 2nd and last phase the participants of the *with GL* group had a statistically significant higher motivation than the participants of the *without GL* group.

After the first changes and additions were presented to the participants, the difference in motivation scores between the two groups is statistically significant ($p=0.000 < \alpha=0.05$). The

[31] H_0: $\mu_{motGL} = \mu_{motw/oGL}$
H2.4 = H_a: $\mu_{motGL} \neq \mu_{motw/oGL}$
U-test:
$p < \alpha$, reject H_0, retain H_a‘motivation declines less when working with GL’
$p > \alpha$, fail to reject H_0, retain ‘no difference in motivation‘

difference in motivation between the two groups in the third phase is not statistically significant, due to strictly observing the confidence level (p=0.057 > α=0.05). After presenting the last additions and changes (at t=120 minutes) the data in Figure 6-16 show a higher motivation for the *with GL* group compared to the *without GL* group in the 4th phase, which again is statistical significant (p=0.000 > α=0.05). Therefore, the data supports the hypothesis of a smaller decline of motivation for the people working with the guidelines, than working without these, when changes are presented.

Comparing the motivation in the different phases

Despite previous results on hypothesis H2.4 the decline of motivation was further analyzed. The motivation of all participants together was analyzed in order to specify the decline of motivation.

For both groups together it was tested, whether the decline in motivation from one phase to the next was statistically significant. Further it was tested, whether differences between 1st and 3rd phase of the test, between 1st and 4th, and between 2nd and 4th phase are statistically significant[32]. The results are presented in Table 6-4, Table 6-5, and Table 6-6.

Table 6-4 Differences in motivation between the phases combined for both groups

	diff phase 1 - 2	diff phase 2 - 3	diff phase 3 - 4	diff phase 1 - 3	diff phase 1 - 4	diff phase 2 - 4
Mann-Whitney-U	2488.5	2103.0*	2687.5	918*	1743.5*	4039*
exact sig. (1-tailed sig.)	.094	.009	.064	.002	.000	.000

*. significant on level α = 0.05 (1-tailed sig.)

The values in Table 6-4 indicate that the decline in motivation from one phase to the next is statistically significant for all the steps, but the one from 3rd to 4th phase. Over a longer period (1st to 3rd, 1st to 4th, 2nd to 4th) the decline of motivation is statistically significant as well. Hence, the analysis supports the statement that changes lead to a decline in motivation; especially over al long period of time working in a changing environment may lead to declining motivation.

To see if there was a difference in the decline of motivation for the *with GL* and the *without GL* group they were analyzed separately. The results of the analyses on the *with GL* and the *without GL* group are presented in Table 6-5 and Table 6-6.

[32] Based on this data it cannot be concluded that changes lead to a faster decline of motivation, than working in an environment without changes. Similar effects might be found on design tasks, where no changes occur.

Table 6-5 Differences in motivation between the phases for *with GL* group

	diff phase 1 - 2	diff phase 2 - 3	diff phase 3 - 4	diff phase 1 - 3	diff phase 1 - 4	diff phase 2 - 4
Mann-Whitney-U	774.5	543.5*	943.5	237.0*	539.5*	1248.0*
exact sig. (1-tailed sig.)	.190	.002	.324	.002	.000	.026

*. significant on level α = 0.05 (1-tailed sig.)

The figures show that differences from on stage to another are only statistically significant for the step from 2nd to 3rd phase. Comparing the motivation over longer periods the decline of motivation show statistically significant effects for all three steps (decline of motivation 1st to 3rd phase: $p_{1\text{-}3}=0.032 < \alpha=0.05$, 1st to 4th phase: $p_{1\text{-}4}=0.032 < \alpha=0.05$ and 2nd to 4th phase: $p_{2\text{-}4}=0.026 < \alpha=0.05$).

Table 6-6 Difference in motivation between the phases for *without GL* group

	diff phase 1 - 2	diff phase 2 - 3	diff phase 3 - 4	diff phase 1 - 3	diff phase 1 - 4	diff phase 2 - 4
Mann-Whitney-U	477.5	459.5	471.5	202.0	314.5*	736.0*
exact sig. (1-tailed sig.)	.135	.222	.071	.082	.000	.000

*. significant on level α = 0.05 (1-tailed sig.)

In the *without GL* group no statistically significant decline of motivation from one phase to the next can be identified. A statistically significant decline can only be observed over longer period as from 1st to 4th phase, and from 2nd to 4th phase.

In summary, working in changing environments on a design task leads to significant decline in motivation no matter whether engineers are working with or without support (see Footnote 32 on page 149). These findings agree with the general statement of Fricke (2006) that changes, which occur during the development process, are perceived as being negative. Figure 6-15 and the analyses (see Table 6-1, Table 6-2) show that the decline in motivation, especially directly after the changes are presented, is larger for the *without GL* group. The data in Table 6-7 shows that there is a statistically significant correlation between the initial motivation of the participants and their motivation during and at the end of the test.

It seems that applying the guidelines has a positive effect on the participants' motivation. The question is, however, why the motivation of the *with GL* group is overall higher, even though the difference in motivation is not statistically significant for most points in time.

Table 6-7 Correlations between motivation at the start (t=0), at the end (t=180) and the motivation during the whole test

			mot t0	mot t180	mot whole test
Kendall-Tau-b	mot t0	correlation coefficient		.367	.643*
		exact sig. (2*(1-tailed sig.))		.075	.001
		N	18	18	18
	mot t180	correlation coefficient	.367		.521*
		exact sig. (2*(1-tailed sig.))	.075		.006
		N	18	18	18
	mot whole test	correlation coefficient	.643*	.521*	
		exact sig. (2*(1-tailed sig.))	.001	.006	
		N	18	18	18

. correlation is on level $\alpha = 0.05$ significant (2(1-tailed sig.)).

The possible explanations for this are diverse. Due to the guideline training the participants of the *with GL* group might have felt more involved in scientific experiment. They might have thought that the study was really not about their personal performance, but about gaining scientific data. In contrast for the *without GL* group the study design was rather similar to an engineering design exam, which is often negatively connoted. They might have felt personally tested instead of participating in an experiment. Hence, the participants of the *without GL* group were less motivated at the beginning of the test and during the whole test; their contentment was lower as well (see Section 6.3.7), which also significantly correlates with the motivation (see Section 6.5).

Statistical significance can be found directly after the changes are presented (significant only for t=30 and t=90; see Table 6-1). Hence, there is not enough evidence to completely reject H2.4 (When working with design guidelines, the motivation declines less when changes occur than when working without the guidelines). However, additional research is highly recommended (see Section 7.3).

6.3.6 **Stress**

In addition to the higher motivation, it was assumed that applying the design guidelines for flexible and robust products reduces the stress of the developers. Therefore hypothesis H2.5 was formulated in Section 5.1: When working *with* the design guidelines, the stress is lower when changes occur than when working *without* the guidelines. In order to evaluate this hypothesis all participants were asked about their current stress level every 10 minutes in questionnaires T0 – T180 (see Table A3 - 1, Table A3 - 2, Table A3 - 3). The participants could rate their personal stress in six steps from *not stressed* to *extremely stressed*. In order to avoid influences of the previous questionnaire, the participants were asked to cover the questionnaires after filling them out.

For better comparison, the mean value of both groups was combined in one graph (Figure 6-17), and linear trend lines included. The mean stress level of both groups was initially at a medium level. It rose for both groups until about the middle of the test (w/o GL 90 min; *with GL* 100 min). Thereafter, a decline of stress could be recognized in both groups. The decline of the *without GL* group was, however, much faster.

At t=30, t=90, and t=120 the changes and additions were presented before the questionnaires were filled out. The effects were as follows: When the first changes and additions were presented the mean stress level of the *with GL* group rose, while that of the *without GL* group declined. The contrary effect could be observed on the next changes at t=90. The stress of the *with GL* group decreased, while the stress of the *without GL* group increased. The last changes (CH120.x) led to a rather small drop of stress for the *with GL* group; the decline of the stress of the *without GL* group was more profound. In Figure 6-17 a strong drop of stress can be recognized at t=120 and the stronger decline of stress of the *without GL* group until the end of the test, which was not due to outliners; it can be identified on all participants of the without GL group.

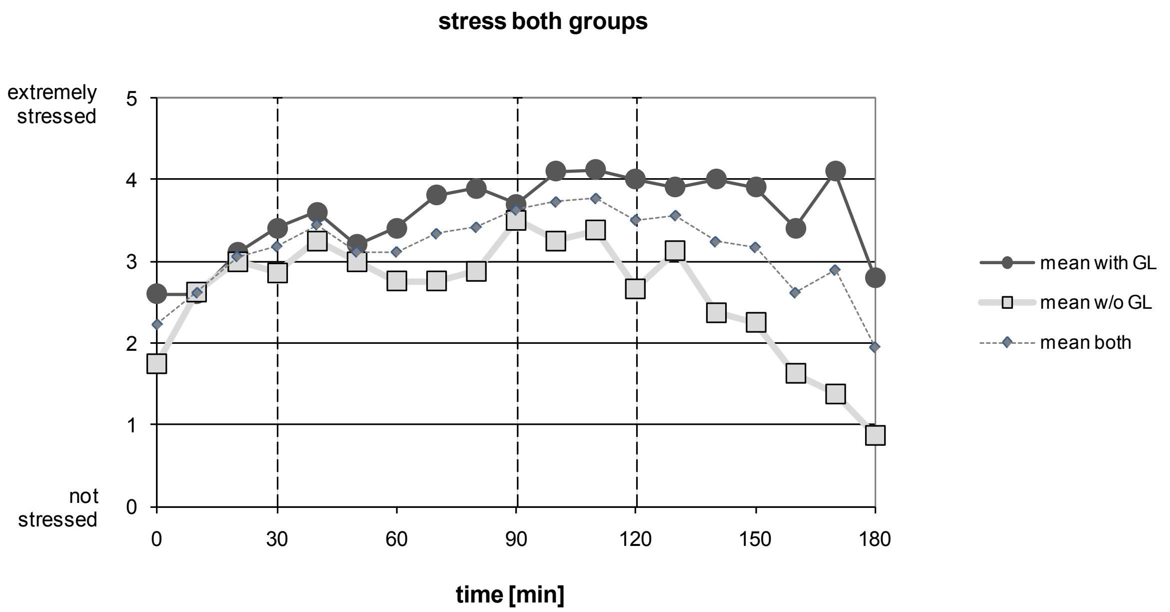

Figure 6-17 Progression of stress for both groups

For a comparison of the stress between the two groups for each point of measurement (every 10 minutes) the Mann-Whitney-U-test was applied[33]. In Table 6-8 and Table 6-9 the results of the analyses are presented.

---

[33] H_0: $\mu_{stressGL} = \mu_{stressw/oGL}$
H2.5 = H_a: $\mu_{stressGL} \neq \mu_{stressw/oGL}$
U-test:
$p < \alpha$, reject H_0, retain H_a'difference in stress'
$p > \alpha$, fail to reject H_0, retain 'no difference in stress'

Table 6-8 Differences in stress from t=0 to t=90

	str t0	str t10	str t20	str t30	str t40	str t50	mot t60	str t70	str t80	str t90
Mann-Whitney-U	26.5	37.5	40	24.5	34.5	36	28	21	17.5	26.5
exact sig. (2*(1-tailed sig.))	.237	.829	1.00	.315	.633	.762	.315	.101	.074	.713

*. significant on level α = 0.05 (2*1-tailed sig.)

Table 6-9 Differences in stress from t=100 to t=180, and stress during whole test

	str t100	str t110	str t120	str t130	str t140	str t150	str t160	str t170	str t180	whole str
Mann-Whitney-U	28	25	13	25	12*	13*	13*	2*	11*	8306*
exact sig. (2*(1-tailed sig.))	.315	.321	.073	.203	.021	.016	.016	.000	.009	.000

*. significant on level α = 0.05 (2*1-tailed sig.)

The level of significance was set to α=0.05 (see 5.2.7). The theory behind the hypothesis would allow single-tailed significance tests. The data shown in Figure 6-17 contradicts the hypothesis of lower stress for the participants of the group working with the guidelines. Therefore here 2-tailed tests were applied: The stress of the *with GL* group was rated higher for every point in time it was evaluated. The differences between the two groups were not statistically significant all the time. Only from t=140 until the end of the test (t=180) the strong decline of stress for the *without GL* group led to significant differences. The stress level of the whole test was also significantly lower for the *without GL* group. Hence, H2.5 (When working with the design guidelines, the stress is lower when changes occur than when working without the guidelines) has to be rejected.

Comparing the stress level of the two groups

While above the stress between both groups was analyzed every 10 minutes, Figure 6-18 illustrates the mean stress level for both groups related to the phases, which were defined by the changes and additions that were presented at 30, 90 and 120 minutes The mean stress level in each phase is based on all questionnaires from all participants in each group that were filled out in each phase.

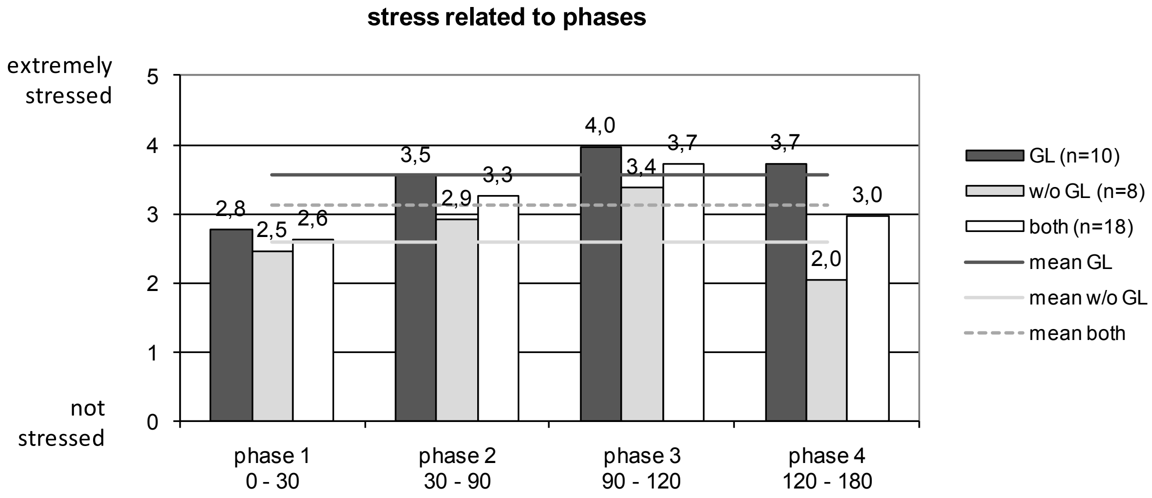

Figure 6-18 Stress of participants related to phases, including contentment of both groups combined

As shown in Figure 6-18 the mean stress level of the *with GL* group was higher. In all four phases the participants of the *with GL* group rated their stress higher than the participants of the *without GL* group. Statistical analyses were carried out to estimate, if the differences in stress related to the phases were statistically significant. Table 6-10 shows the results of a Mann-Whitney-U-test.

Table 6-10 Differences in stress between both groups per phase; phases defined by points in time, when changes are presented

	str phase1	str phase2	str phase3	str phase4
Mann-Whitney-U	320	961.5*	240.5	675.5*
exact sig. (2*(1-tailed sig.))	.469	.005	.120	.000

*. significant on level $\alpha = 0.05$ (2*1-tailed sig.)

The differences in stress levels between the two groups were statistically significant in the 2nd and 4th phase. The differences in the 1st and 3rd phase in stress between working with and without the guidelines are not statistically significant.

Comparing the stress level of the different phases

Even though hypothesis H2.5 (When working with the design guidelines, the stress is lower when changes occur than when working without the guidelines) has to be rejected, the progression of stress is analyzed in more detail. Figure 6-18 highlights the much larger loss in stress for the *without GL* group. Statistical analyses were carried out in order to see if these progressions of stress related to the phases were statistically significant. The results are presented in Table 6-11, Table 6-12 and Table 6-13.

Table 6-11 Differences in stress between the phases for both groups

	diff phase 1 - 2	diff phase 2 - 3	diff phase 3 - 4	diff phase 1 - 3	diff phase 1 - 4	diff phase 2 - 4
Mann-Whitney-U	2086*	2036.5*	2252*	735.5*	2820	5986
exact sig. (2*(1-tailed sig.))	.003	.009	.003	.000	.102	.256

*. significant on level α = 0.05 (2*1-tailed sig.)

The values in Table 6-11 confirm a statistically significant trend of increasing stress for both groups combined from 1st to 2nd and 2nd to 3rd phase and a decline of stress from 3rd to 4th phase, which are visible in Figure 6-18. Moreover, the increase in stress from 1st to 3rd phase is statistically significant as well. The analyzed data does not support a general conclusion that changes always lead to increasing stress. This is due to the decrease in the end of the test, which is discussed at the end of this section.

The results of the analyses on the *with GL* group are presented in Table 6-12 and Table 6-13 below.

Table 6-12 Differences in stress between the phases for the *with GL* group

	diff phase 1 - 2	diff phase 2 - 3	diff phase 3 - 4	diff phase 1 - 3	diff phase 1 - 4	diff phase 2 - 4
Mann-Whitney-U	570*	633*	864	196*	586*	1799
exact sig. (2*(1-tailed sig.))	.004	.037	.265	.000	.000	.234

*. significant on level α = 0.05 (2*1-tailed sig.)

Table 6-12 shows that the trend of increasing stress from 1st to 2nd and from 2nd to 3rd phase, which can be recognized in Figure 6-18, is statistically significant. The decline from 3rd to 4th phase is not statistically significant. The increase from the 1st to 3rd phase is statistically significant, as well as the increase from the 1st to 4th phase. The stress increased during working on the task over a longer period of time. The decreasing stress at the end, which can also be recognized in Figure 6-17 and Figure 6-18, is not statistically significant; general conclusions cannot be derived.

The results for the *without GL* group are shown in Table 6-13.

Table 6-13 Differences in stress between the phases for the *without GL* group

	diff phase 1 - 2	diff phase 2 - 3	diff phase 3 - 4	diff phase 1 - 3	diff phase 1 - 4	diff phase 2 - 4
Mann-Whitney-U	462.5	402	299.5*	166.5*	521.5	729.5*
exact sig. (2*(1-tailed sig.))	.199	.126	.001	.027	.160	.001

*. significant on level α = 0.05 (2*1-tailed sig.)

In contrast to the *with GL* group, no statistical significance for increasing stress from 1st to 2nd and from 2nd to 3rd phase can be found for the *without GL* group. Only the decline from 3rd to 4th phase and the increase over a longer period from 1st to 3rd are statistically significant. There is also a statistically significant decline from 2nd to 4th phase.

It can be concluded that working on a design task in changing environments causes, to some extent, an increase of stress for the developers[34]. In contrast to the theory, on which the hypothesis H2.5 is based, this trend is intensified by the use of the new design guidelines. Table 6-14 shows a statistically significant correlation between the stress of the participants during the whole test and the stress at the end of it (t=180). There are no statistically significant correlations between the initial stress (t=180) and the stress over the whole study or between the initial stress and the stress at the end of the test (t=180).

Table 6-14 Correlations between stress at the start (t=0), at the end (t=180) and stress during the whole test

			str t0	str t180	str whole test
Kendall-Tau-b	str t0	correlation coefficient	1.000	.057	1.000*
		exact sig. (2*(1-tailed sig.))		.776	.000
		N	18	18	18
	str t180	correlation coefficient	.057	1.000	.057
		exact sig. (2*(1-tailed sig.))	.776		.776
		N	18	18	18
	str whole test	correlation coefficient	1.000*	.057	1.000
		exact sig. (2*(1-tailed sig.))	.000	.776	
		N	18	18	334

. correlation is on level $\alpha = 0.05$ significant (2(1-tailed sig.)).

In summary, working in changing environments tends to increase the stress. Whether this trend is stronger than working on a design task without changes cannot be derived from the current data. The addition of the guidelines increased the participants' stress compared to those not working with the guidelines. Therefore the hypothesis H2.5 has to be rejected. The opposite trend is statistically supported by the collected data. It can be assumed that the participants were not familiar enough working with the guidelines. Reading the guidelines, understanding and trying to apply these in addition to working on a design task provided additional stress. The benefits, which should be achieved by applying the guidelines, did not seem to compensate for this downside. Positive effects on the stress by applying the guidelines might occur in the long term, either on longer and real projects or when product developers are more familiar with the guidelines, e.g. by more intensive teaching or more frequent application of the guidelines. This however has to be confirmed in further research (see Section 7.3).

For both groups the stress declined at the end of the study. Several reasons for this can be discussed. First of all, the last questionnaire (T180) was filled out after the test. The work on the

[34] It cannot be concluded that working in changing environments leads to more stress than working on a design task that is clearly defined at the beginning and not subject to changes. This comparison is not made in the described study.

design task was finished (even though the designs were not). This naturally led to more relaxed participants with a declining stress level. Taking this data out of the calculation, the effect of declining stress at the end of the study is less definite, but still recognizable; especially in the *without GL* group. One reason for this could be the participants' assumption, that after t=120 no more changes would be presented to them, as two thirds of the study are passed already, even though they could not be sure of this during the test. A more likely cause might be an attitude of giving up. Recognizing that they would not be able to finish the design task in time could have led to resignation. The participants no longer tried to finish the task; hence their stress declined. This explanation would support the hypothesis of the beneficial effects of working with the guidelines on the developers' motivation, as the effect of giving up is less distinctive for the *with GL* group. The *with GL* group might have been more optimistic and motivated about finishing the task and thus continued the work even with high stress in the later phases. The participants of the *with GL* group were more content with their work and hence continued working instead of giving up. This, however, is analyzed in the following Section 6.3.7.

6.3.7 **Contentment**

According to the theory the application of the guidelines is assumed to lead to higher contentment with the work than when no guidelines are used. This is expressed in hypothesis H2.6: When working with the design guidelines the contentment with the own work is higher than when working without the guidelines. In order to evaluate this hypothesis all participants were asked about their current contentment every 10 minutes during the test. Questionnaires were used to collect the data (T0 – T180, see Table A3 - 1, Table A3 - 2, Table A3 - 3). The participants were able to rate their personal contentment in six steps from *not content* to *extremely content*. In order to not bias the current evaluation with the previous one, the participants were asked to cover the questionnaires after filling out. This way the progression of the participants' contentment could be documented. Figure 6-19 illustrates the progression of the participants of the *with GL* group and the *without GL* group separately.

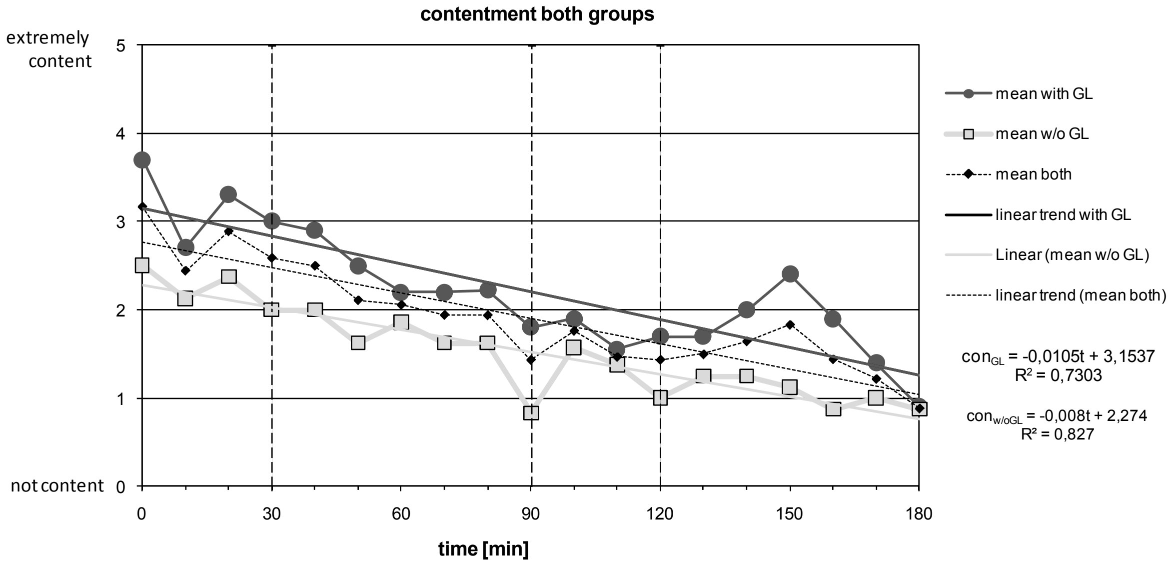

Figure 6-19 Progression of contentment for both groups

For better comparison the mean values of both groups are combined in one graph (Figure 6-19). The linear trends are included. Regression analyses show a similar decline of contentment for both groups during the test (-0.0105t for the *with GL* group to -0.008t for the *without GL* group). One major difference is that the *with GL* group started with a higher contentment level. Given a similar decline, the *with GL* group ended up with higher contentment as well, even though their decline was slightly more profound. The curves in Figure 6-19 show that the presented changes and additions can lead (for a short period) to a faster decline of contentment. This is especially visible for both groups at t=90 and for the *without GL* group at t=120.

For a comparison of the contentment between the two groups for each point of measurement (every 10 minutes) a Mann-Whitney-U test was applied. In Table 6-15 and Table 6-16 the results of the analyses are presented.

Table 6-15 Differences in contentment from t=0 to t=90

	cont t0	cont t10	cont t20	cont t30	cont t40	cont t50	cont t60	cont t70	cont t80	cont t90
Mann-Whitney-U	16.5*	28.5	20.5*	18.5	25	23	30.5	29	31	12.5*
exact sig. (1-tailed sig.)	.017	.158	.042	.055	.102	.073	.335	.180	.337	.028

*. significant on level α = 0.05 (1-tailed sig.)

Table 6-16 Differences in contentment from t=100 to t=180, and contentment during whole test

	cont t100	cont t110	cont t120	cont t130	cont t140	cont t150	cont t160	cont t170	cont t180	whole cont
Mann-Whitney-U	29	31.5	19.5	30.5	23	17*	20*	30	39.5	9422.5*
exact sig. (1-tailed sig.)	.301	.337	.132	.204	.118	.022	.042	.204	.483	.000

*. significant on level α = 0.05 (1-tailed sig.)

The level of significance is set to α=0.05 as there is a theory based hypothesis, which proclaims a difference in one direction (lower contentment for the *without GL* group). With these values, statistically significant differences between the *with* and the *without GL* group can be found at t=0, t=20, t=90, t=150, and t=160[35]. Even though the contentment was not significantly higher for every point in time it was measured with the questionnaires, the contentment level over the whole test period was significantly higher for the *with GL* group. This supports hypothesis H2.6 (When working with the design guidelines the contentment with the own work is higher than when working without the guidelines.). It has to be assumed that the guideline application is the reason for the higher contentment of the *with GL* group, as all participants did apply several guidelines during the test (see Section 6.4.3). However, there is no statistically significant correlation between the number of guideline applications and the contentment of the participants (see Table 6-23).

It was said earlier that a decline of contentment could be identified when changes and additions were presented. The contentment was not only measured directly after the changes and additions were presented, but every 10 minutes: Statistically significant differences between the *with* and the *without GL* group can already be found before the first changes and additions are presented to the participants, for example at the beginning of the test at t=0. Further statistically significant differences can be found in the period between the first and last time changes were presented to the participants (e.g. t=50), and after the last changes (t=150). Therefore, the positive effects from applying the guidelines were not limited to the moment when changes occur, but could be recognized during the whole test.

Comparing the contentment of the two groups

In the previous paragraphs the contentment between both groups was analyzed for every 10 minutes. The figure below illustrates the mean contentment level of the participants from both groups related to the phases (see Figure 6-20). The phases were defined by the changes and

[35] H_0: $\mu_{contGL} = \mu_{contw/oGL}$
H2.6 = H_a: $\mu_{contGL} \neq \mu_{contw/oGL}$
U-test:
$p < \alpha$, reject H_0, retain H_a‘contentment higher when working with GL’ for t=0, t=20, t=90, t=150, t=160
$p > \alpha$, thus fail to reject H_0, retain ‘no difference in contentment‘for t≠0, t≠20, t≠90min, t≠150, t≠160

additions, which were presented at 30, 90 and 120 minutes. The mean contentment level in each phase was based on all questionnaires from all participants in each group.

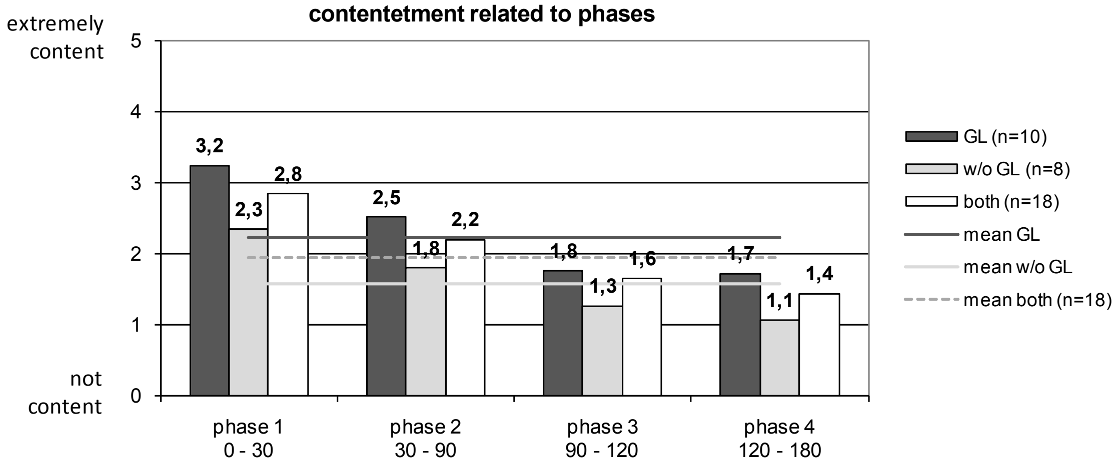

Figure 6-20 Contentment of participants related to phases, including contentment of both groups together

The mean contentment was significantly higher for the *with GL* group (Table 6-16). In all four phases the participants of the *with GL* group rated their contentment higher than the participants of the *without GL* group. The results of a Mann-Whitney-U-test show that the difference in contentment between the two groups was statistically significant in all phases (Table 6-17).

Table 6-17 Differences in contentment between both groups per phase; phases defined by points in time, when changes are presented

	cont phase1	cont phase2	cont phase3	cont phase4
Mann-Whitney-U	195.5*	944.5*	219*	1243*
exact sig. (1-tailed sig.)	.002	.003	.041	.001

*. significant on level $\alpha = 0.05$ (1-tailed sig.)

Therefore, this analysis supports the beneficial effects on the contentment of the participants when applying the design guidelines in changing environments. There is not enough evidence to reject H2.6 (When working with the design guidelines the contentment with the own work is higher than when working without the guidelines).

Comparing the contentment level of the different phases

Hypothesis H2.6 is further analyzed. As a decline of contentment from each phase to the next can be recognized for both groups independently, this decline can also be observed when both groups are jointly analyzed (Figure 6-19, Figure 6-20). Mann-Whitney-U tests were applied for both groups together, for the *with GL* group, and for the *without GL* group, if the decline of contentment from one phase to the next is statistically significant. In addition analyzes were carried out to see whether the differences between the 1st and 3rd, between the 1st and 4th, and between the 2nd and 4th phase are statistically significant. The results are presented in Table 6-18, Table 6-19, and Table 6-20 below.

Table 6-18 Difference in contentment between the phases for both groups together

	diff phase 1 - 2	diff phase 2 - 3	diff phase 3 - 4	diff phase 1 - 3	diff phase 1 - 4	diff phase 2 - 4
Mann-Whitney-U	1955*	1768.5*	2876	601*	1325*	3992.5*
exact sig. (1-tailed sig.)	.001	.001	.245	.001	.000	.000

*. significant on level α = 0.05 (1-tailed sig.)

The values in Table 6-18 indicate that, when both groups are taken together, the decline of contentment from the 1st to 2nd and from the 2nd to 3rd phase are statistically significant, but not for the difference between the 3rd and 4th phase. Analyzing the longer periods (1st to 3rd, 1st to 4th, 2nd to 4th) the decline of contentment was statistically significant for the difference between 1st and 3rd, 1st and 4th phase as well as the difference between 2nd and 4th phase. Hence, the analyzed data does not support the statement that changes always lead to a decline of motivation. However, two of the three times when changes and additions were presented to the participants the contentment significantly declined. In the long term working in a changing environment led to declining contentment as well (see Footnote 32 on page 149).

To see if there is a difference in the decline of contentment for the *with GL* and the *without GL* group they are analyzed separately. The results of the analyses on the *with GL* group are presented in Table 6-19.

Table 6-19 Difference in contentment between the phases for *with GL* group

	diff phase 1 - 2	diff phase 2 - 3	diff phase 3 - 4	diff phase 1 - 3	diff phase 1 - 4	diff phase 2 - 4
Mann-Whitney-U	504.5*	519*	970.5	140*	337.5*	1203.5*
exact sig. (1-tailed sig.)	.001	.001	.404	.000	.000	.000

*. significant on level α = 0.05 (1-tailed sig.)

Table 6-19 shows that there is a statistically significant difference of contentment for the *with GL* group between the 1st and the 2nd phase and from 2nd to 3rd phase. The decline of contentment from 3rd to 4th phase is not statistically significant. The longer term analysis from 1st to 3rd, 1st to 4th and 2nd to 4th phase were also statistically significant. Therefore it can be assumed that (in the long term) working in changing environments leads to a decline of contentment, when working with the design guidelines.

Table 6-20 Difference in contentment between the phases for *without GL* group

	diff phase 1 - 2	diff phase 2 - 3	diff phase 3 - 4	diff phase 1 - 3	diff phase 1 - 4	diff phase 2 - 4
Mann-Whitney-U	425	358.5*	514.5	128*	265*	806*
exact sig. (1-tailed sig.)	.050	.042	.258	.002	.000	.001

*. significant on level α = 0.05 (1-tailed sig.)

The differences on contentment for the *without GL* group are statistically significant for the step from 2nd to 3rd phase and when analyzing longer periods from 1st to 3rd, 1st to 4th and 2nd to 4th phase. Due to strictly observing the confidence level ($p=0.050$ not $< \alpha=0.05$) the decline in contentment from 1st to 2nd phase is not highlighted as statistically significant.

The decline of contentment of the participants from the *with GL* and from the *without GL* group was almost identical. However, during the whole study the contentment of the *with GL* group was above the contentment of the *without GL* group (Figure 6-20). The reason for this can be the same as argued at the end of Section: Due to the guideline training the participants of the *with GL* group might have felt more involved in scientific experiment. They might have thought that the study was really not about their personal performance, but about gaining scientific data. In contrast for the *without GL* group the study design was rather similar to an engineering design exam, which is often negatively connoted. They might have felt personally tested instead of participating in an experiment. Hence, the participants of the *without GL* group were less content, not only with their own work, but also with the overall test participation, at the beginning of the test and during the whole test; their motivation was lower as well (see Section 6.3.7), which also significantly correlates with the contentment (see Section 6.5).

In summary, the evaluation of hypothesis H2.6 (When working with the design guidelines the contentment with the own work is higher than when working without the guidelines.) is ambiguous: Comparing the contentment of the *with* and the *without GL* group separately for every ten minutes (see Table 6-15 and Table 6-16) H2.6 had to be rejected. In contrast, when comparing the contentment of related to the phases the contentment of the *without GL* group was significantly lower than of the *with GL* group (see Table 6-17). Hence, this way there is not enough evidence to reject hypothesis H2.6.

Correlations

Comparing the contentment of the participants of the two groups related to the phases defined by the changes the differences are statistically significant for the whole test. Table 6-21 indicates that there is a significant correlation between the initial contentment at the beginning of the test (t=0) and the mean contentment during the whole test.

Table 6-21 Correlations between contentment at the start (t=0), at the end (t=180) and the contentment during the whole test

			cont t0	cont t180	cont whole test
Kendall-Tau-b	cont t0	correlation coefficient	1.000	.183	1.000*
		exact sig. (2*(1-tailed sig.))	.	.378	.000
		N	18	18	18
	cont t180	correlation coefficient	.183	1.000	.183
		exact sig. (2*(1-tailed sig.))	.378	.	.378
		N	18	18	18
	cont whole test	correlation coefficient	1.000*	.183	1.000
		exact sig. (2*(1-tailed sig.))	.000	.378	.
		N	18	18	332

. correlation is on level $\alpha = 0.05$ significant (2(1-tailed sig.)).

The theory, on which hypothesis H2.6 is based, explains, why the contentment of participants, which are supported by the guidelines, is higher in comparison to the *without GL* group. However, if the argumentation regarding the higher initial contentment of the *with GL* group is correct, the collected data cannot explain why the decline of contentment is slightly stronger (see Figure 6-19). This has to be subject of future research (see Section 7.3).

6.3.8 Conclusion

Research question RQ2 was formulated as follows:

> RQ2: Does flexible and robust product design, which is achieved by the application of the design guidelines, lead to better handling of changes during the development process?

Six hypotheses have been formulated based on this. The previous sections aim at evaluating these hypotheses in order to answer the research question. The results on the evaluation of the hypotheses are inconsistent. H2.1 about the sooner implementation of changes could not be answered due to insufficient data. H2.2 on the faster implementation of changes had to be rejected. Moreover, the analyses could not confirm that the application of the guidelines led to less negative effects, when changes were presented, and that the stress level of the developers working with the guidelines in a changing environment is lower (H2.3, H2.5). The evaluation of hypothesis H2.4 on the motivation of the participants led to mixed results: For both groups the decline in motivation is statistically significant; the regression analysis shows that the decline of the *with GL* group is slightly faster. Especially directly after presenting the changes at t=30 and t=90 the motivation of the *with GL* group was statistically significantly higher. The mean motivation during the whole test was statistically significantly higher for the *with GL* group as well. However, analyzing the motivation of the participants for every point in time singularly the results are less definite. Moreover, the evaluation of the last hypothesis H2.6 about the contentment led to mixed results as well.

The conclusion on RQ2 is ambiguous: the flexible and robust product design, which is achieved by the application of the design guidelines, can lead to better handling of changes during the development process. However, the positive effects are not statistically significant for all points in time and for all hypotheses, which were formulated. Moreover, negative effects, like higher stress due to the guideline application cannot be ignored. For a more explicit answer of RQ2 more research is proposed (see Section 7.3).

6.4 RQ3: Are the Guidelines a Suitable Support?

This section aims at answering research question RQ3, which is:

RQ3: Is the developed support suitable for developing flexible and robust products?

The data from the questionnaires (T180-1 to T180-4) shown in Table A3 - 3ff. were analyzed. The evaluation of the three hypotheses, which were derived from the research question, is described in Sections 6.4.1 to 6.4.3.

6.4.1 **Understanding Guidelines**

Hypothesis H3.1 is: The newly generated design guidelines are easy to understand. After three hours working on the design task, the participants of the *with GL* group were asked about the design guidelines in questionnaire T180 (Table A3 - 3ff.). Separately for each guideline and together for the guideline set as a whole the participants had to evaluate their understanding of the design guidelines on a scale of 0 *do not understand at all* to 5 *completely understand*. Figure 6-21 below illustrates the results, showing the mean values regarding the understanding for each single guideline given by the participants.

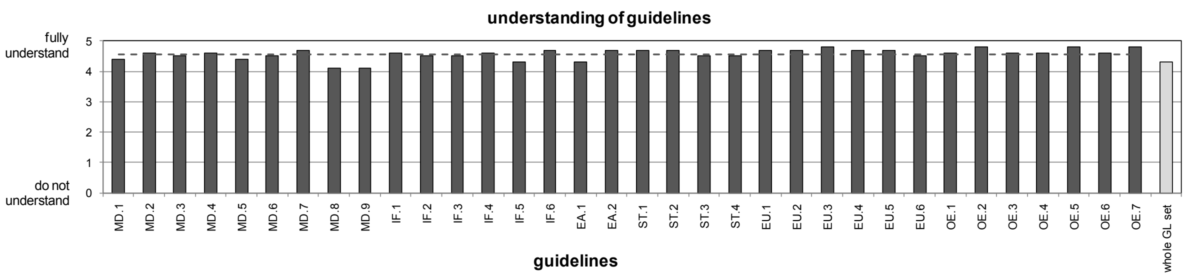

Figure 6-21 Understanding of guidelines

The figure indicates that in general the participants working with the design guidelines state that they understand the guidelines well (mean 4.57 of 5, with 5 meaning *completely understand*). However, it cannot be clarified, whether the participants really understand the guidelines or if they only had the subjective feeling of understanding them. It is also possible that the answers were given to please the researcher. This would explain the ceiling effect, which can be recognized in Figure 6-21. However, other questions (e.g. "How do you rate the support provided by the guideline?") in the questionnaire were not answered so univocally positively; the mean was lower and variation of the given answers was higher (see Section 6.4.2). Nevertheless, the understanding of the design guidelines was rated high. Therefore it is concluded that based on the given data[36], there is not enough evidence to reject hypothesis H3.1, which is therefore retained, even though more specific future research on this topic is advised (see Section 7.3).

6.4.2 **Support by Guidelines**

In Section 5.1 the hypothesis H3.2 was formulated as follows: Applying the newly generated design guidelines supports the product developer when developing products in changing environments. For each guideline separately and for the guideline-set as a whole, the participants had to evaluate the given support on a scale of 0 *not supported at all* to 5 *well supported*. Figure 6-22 illustrates the results.

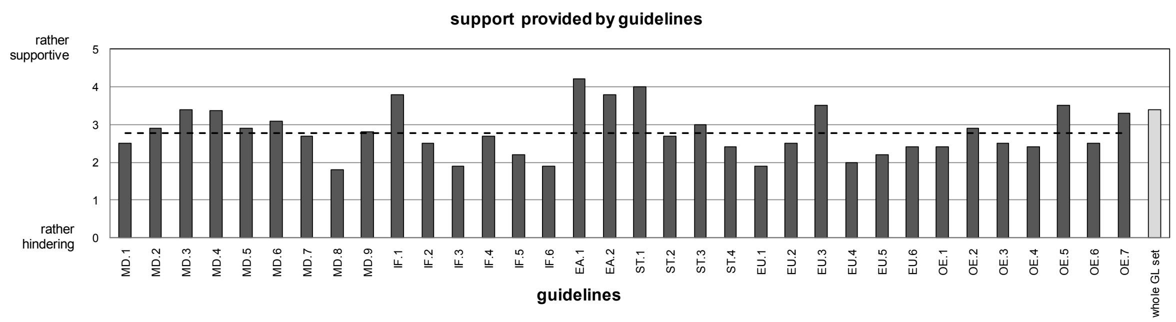

Figure 6-22 Support provided by guidelines

The support provided by the guidelines was rated with a mean value of 2.78 on a scale of 0 to 5. Comparisons with other supporting tools or other design guidelines were not carried out. Thus, it cannot be clarified, whether the value of 2.78 is very good or not. The guideline set as a whole was rated with a mean score of 3.4, which was higher than the mean value of the single guidelines. In comparison to the answers related to hypothesis H3.1 the answers related to H3.2 are less clearly supporting the hypothesis.

[36] Asking the participants during and after the training on the design guidelines (see Section 5.2.5) led to positive feedback as well, supporting the high level of understanding

The participants were also asked, whether they considered applying the guidelines an advantage or a disadvantage[37]. Five out of ten stated that the guidelines are *rather advantageous* compared to three, who stated that the guidelines are *rather less advantageous* (two participants did not answer this question). The opposite question, whether the guidelines were more or less disadvantageous, shows inconsistency: Five of ten participants claimed the guidelines as rather more disadvantageous compared to 4 of 10, who rated them as rather less disadvantageous; one participant did not answer this question. No general conclusion can be drawn from this data.

The stress while working on the design task was rated significantly higher for the *with GL* group than for the *without GL* group (Section 6.3.6). The participants from the *with GL* group were asked afterwards, if they considered applying the guidelines an additional stress factor. The results are shown in Figure 6-23.

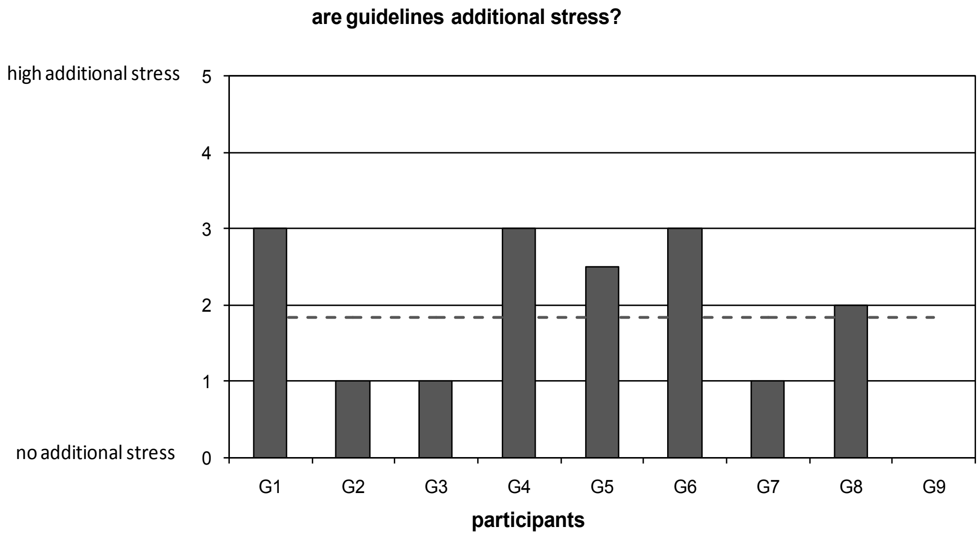

Figure 6-23 Guidelines and additional stress[38]

The participants rated the additional stress level with a mean value of 1.83 (with 0 is no addition stress and 5 is high additional stress. One participant (G9) stated that the guidelines did not lead to additional stress. Three of the participants rate it rather low (score 1). Again, there is the possibility of biased and benevolent data as a favor to the researcher.

The answers on the question if the guidelines are considered as higher stress do only significantly correlate with the motivation at t=0 (see Section 6.5). As the correlation is negative,

[37] Questions 12 and 13 in questionnaire T180-2 (Table A3 - 4), which were formulated as open questions:
12. Did you have advantages due to applying the guidelines? What kind of?
13. Did you have disadvantages due to applying the guidelines? What kind of?

[38] Participant G10 did not answer the last questionnaire. Therefore G10 is not shown in this and the following figures in order not to confuse with the answer, which equal 0 on the horizontal-axis.

this means that the participants, which were higher motivated at the beginning of the test rated the additional stress due to the guidelines lower afterwards. All other correlations are not statistically significant.

After the test the participants of the *with GL* group were also asked, if they agree that the new guidelines were useful for the development of flexible products; the participants could mark in six steps between *do not agree at all* (0 points) and *completely agree* (5 points). The results are shown in Figure 6-24.

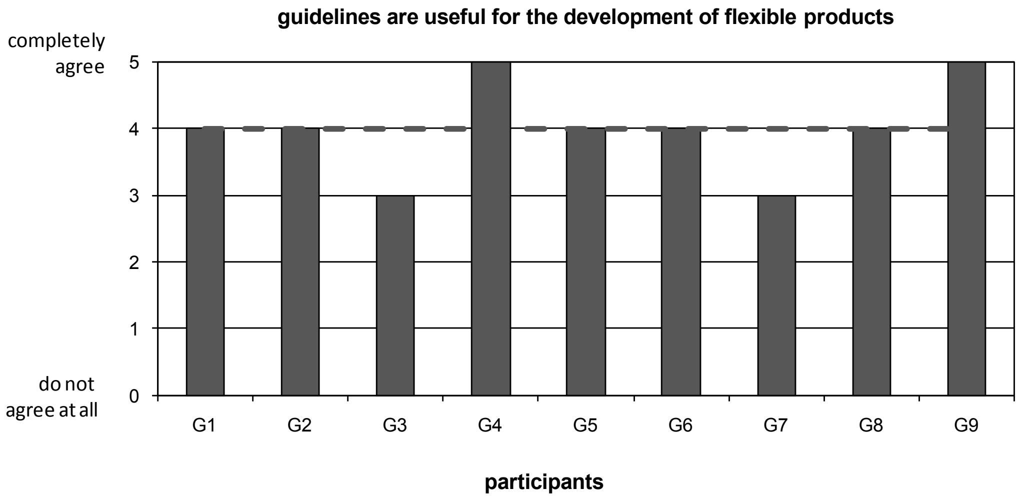

Figure 6-24 Guidelines useful for the development of flexible products? (see Footnote 38)

The mean score was 4 on a scale of 0 to 5 with 0 being defined as *do not agree at all*. Two participants rated it slightly lower (score 3) and two participants completely agreed with the usefulness of the guidelines for the development of flexible products.

The guidelines were considered useful for the development of products for changing environments. Understandability was rated high. The additional stress due to the guideline application was rated as being acceptable. However, the support provided by the guidelines is less positive. The data shown in Figure 6-24 significantly correlates with the answers on the question, if the guideline set is considered a good support for developing flexible products, which was asked after the test. This means that the participants, who more agreed to the statement that the guidelines are useful for the development of flexible products, also rated the support provided by the guidelines higher after the test. All other correlations are not statistically significant (see Section 6.5).

Based on this data a precise evaluation on hypothesis H3.2 (Applying the newly generated design guidelines supports the product developer when developing products in changing environments) is difficult, the result is ambiguous. Here it is concluded that the newly generated design guidelines are supportive to the product developer, as stated in H3.2. The support, however, could be improved maybe by being more specific or context related.

In addition to the support, the participants were asked, whether or not they agreed with the underlying idea of developing flexible products in order to handle changes (question 15 in T180-2, Table A3 - 4). Again a six step scale was used. The extremes were 0 *do not agree at all* and 5 *completely agree*. The results are shown in Figure 6-25.

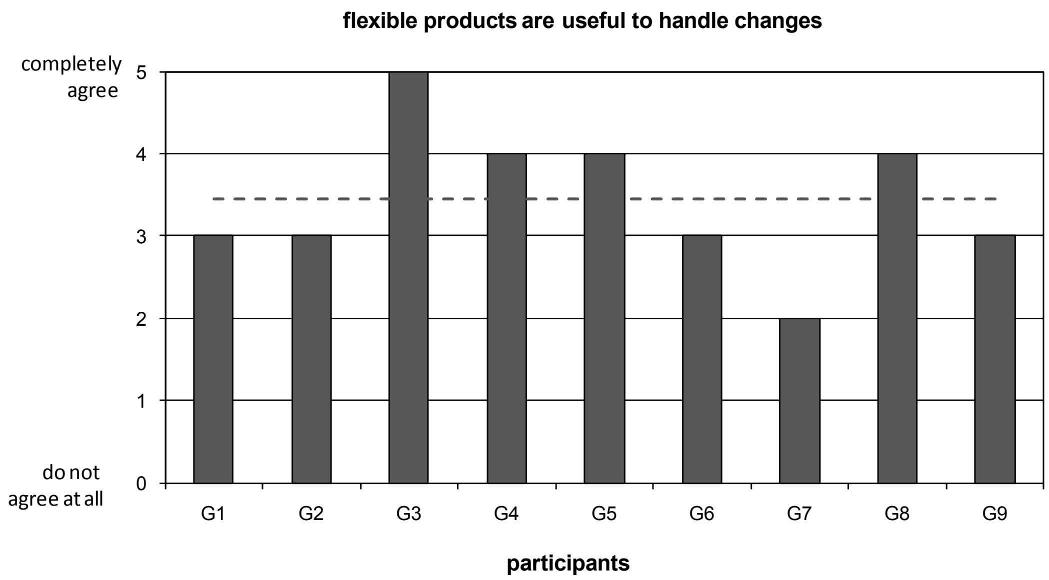

Figure 6-25 Flexible products useful for handling changes? (see Footnote 38 on page 166)

The mean result was 3.44 out of 5. The answers were less positive than on the usefulness of the guidelines for the development of flexible products. The participants less agreed that the basic idea of developing flexible and robust products in order to handle changes is useful. Nevertheless the mean value was above the arithmetic mean value of 2.5. The participants of the *with GL* group evaluate the approach of developing flexible products to handle changes with a slight trend towards *flexible products are useful to handle changes*. The potential of the idea is recognized by the participants.

6.4.3 Application of Guidelines – Time, number, participant

Hypothesis H3.3 was formulated in Section 5.1 as: The newly generated design guidelines can be applied in earlier as well as in later phases of the development process. The participants of the *with GL* group were asked to mark on the guideline sheet, when they intentionally used a guideline (Figure 5-8). Figure 6-19 shows the sum of all intentional guideline applications of the *with GL* participants in twenty minute intervals, which are based on the color changes of the pens (multiple responses on the same guideline are possible).

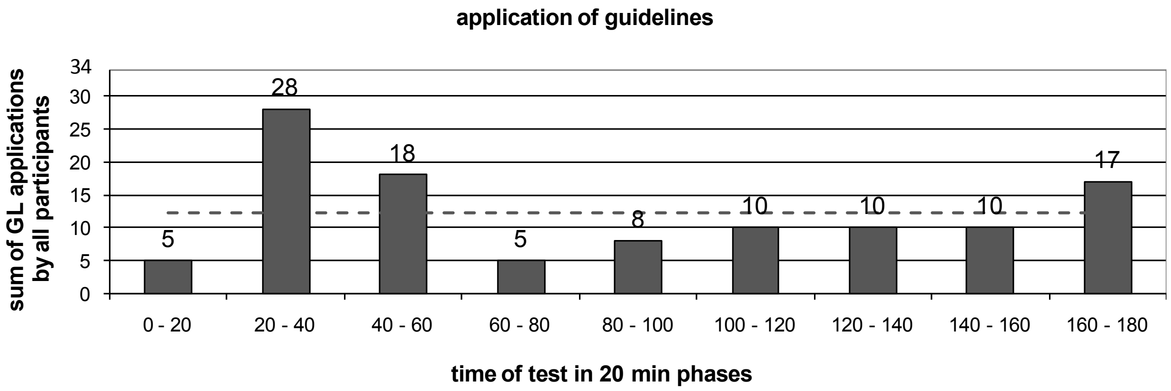

Figure 6-26 Guideline applications over time

Most guidelines were used in the middle of the concept phase from 20 to 40 minutes. The ten participants applied 28 guidelines in this period. In the next period (40-60min) 18 guidelines were used. During the last phase (160-180min), the participants also indicated a relatively high number of 17 guideline applications. In the 9 phases the mean was 12 guideline applications per 20 minutes for the ten participants. The mean number of guideline applications was 11.4 per participant during the whole test. Even though the guidelines could be used in the later phases of the development process, here another effect is assumed: Before all papers were finally collected, the participants remembered to mark all guidelines they used during the study. Hence, the number of applications rose in the last phase, but no application could be found on the drawing to support this data. Therefore the main application time of the guideline was in the early phases of the development process. Hence there is not enough evidence to reject hypothesis H3.3.

Figure 6-27 shows which guideline was applied and how often. On average, the 34 guidelines were applied 3.5 times. The highest number of applications per guideline was 10 (DA.1 Plan definite (dis-) connecting devices and consider disconnecting from the beginning). Some guidelines were not used at all (MD.8, IF.5, IF.6, ST.2, OE.4), others only once or twice. The reasons for this are probably diverse. As shown in Table 6-22 there is a significant correlation between the support provided by a guideline (rated by the participants) and the number of applications in the test. Moreover, it can be assumed that the number of guideline applications strongly depends on the specific design task and other context factors like the product domain or the personal experience of the product developer with a single guideline.

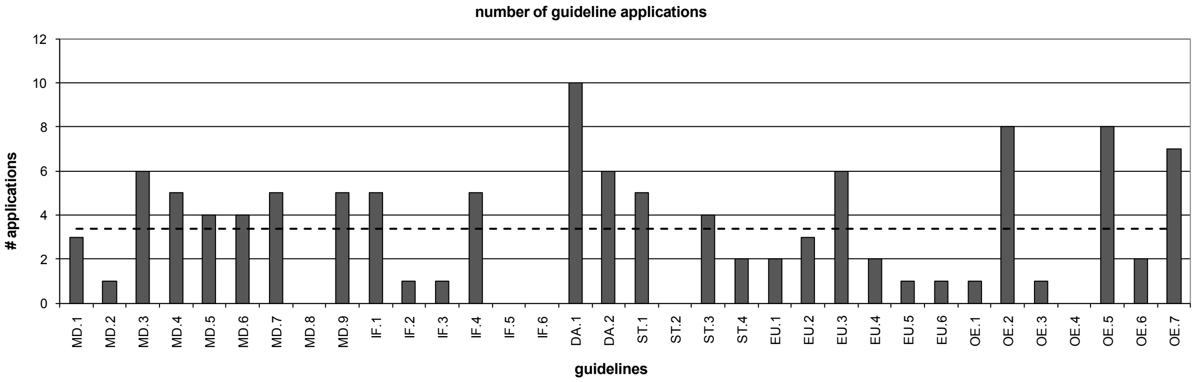

Figure 6-27 Number of guideline applications

The application was strongly related to the design task. Extremely high or low numbers of applications do not say something about the quality of the guidelines. However, it can be assumed, that in general there are differences between the quality of the guidelines and the support they provide.

Kendall-T-b test was applied to check if there are statistically significant correlations between the number the single guidelines are applied (see Figure 6-27), the considered support provided by the guideline and the rate of understanding of guidelines (see Figure 6-21). The results are shown in Table 6-22.

Table 6-22 Correlation of GL understanding, GL support and number of GL applications

			GL understanding	GL support	# of GL applications
Kendall-Tau-b	GL understanding	correlation coefficient	1.000	.126	.209
		exact sig. (2*(1-tailed sig.))	.	.337	.121
		N	34	34	34
	GL support	correlation coefficient	.126	1.000	.644*
		exact sig. (2*(1-tailed sig.))	.337	.	.000
		N	34	34	34
	# of GL applications	correlation coefficient	.209	.644*	1.000
		exact sig. (2*(1-tailed sig.))	.121	.000	.
		N	34	34	34

. correlation is on level $\alpha = 0.05$ significant (2(1-tailed sig.)).

The figures show that there is a statistically significant correlation between the number of times a guideline was applied and the considered support of the single guideline. It can be assumed that the higher support provided by the guideline led to a higher number of applications, not vice versa. However, the test was carried out double sided as there were no specific hypotheses formulated beforehand. The other correlations are not statistically significant.

Figure 6-28 below illustrates how many guidelines the different participants used during the test. The maximum number of guideline applications was 23 by the participants G5 and G10 (using 17 and 18 different guidelines respectively); the minimum number of guideline applications was three by participant G6 (two different guidelines). The mean number of intentionally used guidelines was 11.4 for the ten participants working with design guidelines (with an average of 9.5 different guidelines chosen from the set of 34 guidelines).

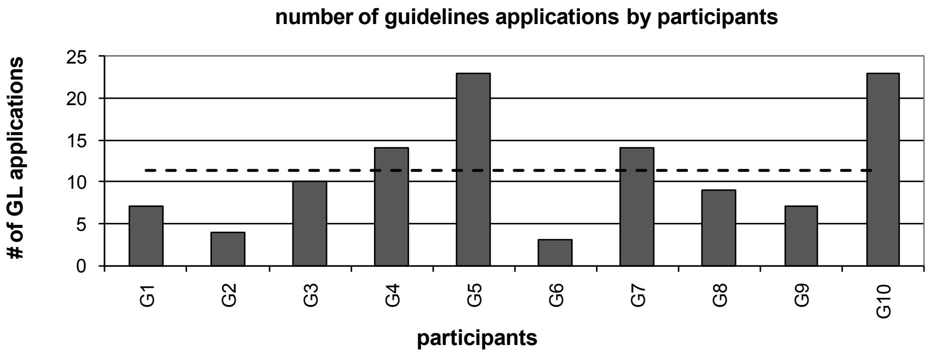

Figure 6-28 Number of guidelines applied by participants

The high number of guideline applications of G5 and G10 is noticeable. These two participants were outliers in the time for the concept as well, as they needed 155 and 95 min for the concept, while the mean of all participants was 88 min and the mean of the *with GL* group 73 minutes (see Section 6.3.2). The analyzes of the data using Kendall-T-b show, however, that this correlation between concept time and number of guideline applications (see Section 6.5) is not statistically significant ($p=0.097> \alpha=0.05$). Further, the data indicates a correlation between the term of study and the number of guideline applications (see Section 6.5), as the more experienced the participant were (the longer they studied), the more guidelines the participants applied. However, this correlation is not statistically significant ($p=0.098> \alpha=0.05$). The initially calculated skill value, the quality of the results and the mentioned additional stress due to the guidelines, do not significantly correlate to the number of guidelines applied.

After the test, participants of both groups were asked about their two most positive and two most negative experiences during the test (questions 9 and 10 in T180-2, see Table A3 - 4). The answers to this open-ended question were diverse, e.g. "planned rolls already before the changes were presented" (participant of the *with GL* group on positive experiences) or "the changes!!!" (participant of the *without GL* group on negative experiences). All answers were clustered in 3 groups for an initial comparison. The 3 groups were: *test design*; *flexibility and changes* and *own skills and results*. The groups were valid for positive experiences as well as for negative ones; thus, the two examples on positive and negative changes above both belong to the group *flexibility and* *changes*. The results are shown in Figure 6-29. The number of answers given per question and group (e.g. positive experiences of the *with GL* group) is divided by the total number of answers given per group in order to ease comparison.

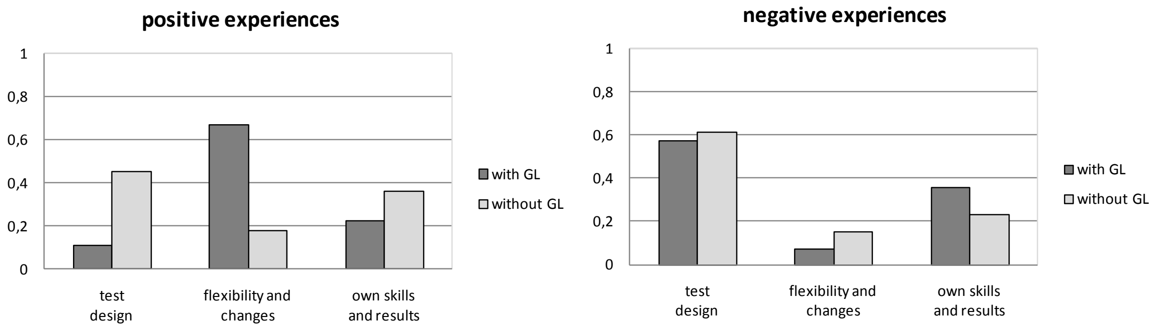

Figure 6-29 Positive and negative experiences of the participants during the test

Even though each participant was asked to give two answers to each question the overall number of answers is quite limited as not all participants answered these questions. Thus, all participants of the *with GL* group (n=10) mentioned 8 positive and 13 negative experiences during the test. The participants of the *without GL* group (n=8) gave 11 answers on the positive experiences and 13 on the negative ones. The absolute number of answers was 45 (of 72). Due to the low number of answers within each group no general conclusion can be drawn.

It is noticeable however, that especially participants of the *with GL* group mentioned the flexibility and the easy handling of the changes as a positive experience, while the participants of the *without GL* group highlighted the test design as positive. The answers given on the most negative experiences were more balanced between the groups; the test design (including e.g. limited time and the pencils) were most often mentioned in both groups.

6.4.4 **Conclusion**

The derived guidelines form new support for developing flexible and robust products in changing environments. Initial training could be carried out in as little as 80 min. After this short training, the users had the feeling that they understood the guidelines. The users were able to apply most of them. The application showed beneficial effects e.g. on the change implementation, the developers' motivation and their contentment (see Section 6.3). These positive effects of the guideline application were not always as unambiguous as formulated in the hypotheses. In some points the application clearly led to negative effects, e.g. on the developers' stress.

Nevertheless, the set of 34 design guidelines can be considered an applicable support. The guidelines are a serious support for systematic product development in changing environments.

However, application of the new guidelines still has its downsides. The users' evaluation of the support is positive. The basic idea of handling changes with flexible and robust product design is agreed to be useful, yet not too optimistically. Comparisons with other supports, tools and methods will have to be carried out to see whether the guidelines are just sufficient or provide a better support than other approaches.

6.5 Correlations

The data, which was collected in the study with the questionnaires, was analyzed for further interesting findings. Most of the data was ordinal scale. It was checked for correlations with Kendall-T-b. Kendall-T-b is robust against extrema, which is good, as the analysis was neither theory- nor hypothesis driven (Bühl & Zöfel 1999). Double sided tests were carried out with a significance level of $\alpha=0.05$. The total number of cases was n=18; for the guideline-related cases the number of cases was n=10 unless otherwise indicated in the table. Table 6-23 below shows the results of Kendall-T-b for the correlations of the most important data of the study. The statistically significant effects are highlighted in the table.

Table 6-23 Correlations

. Variables are mathematically linked (see section ...)

s ga with e	in ir	of d	of s ur	stu te	c ha u fl	p fle f (	s	us of n	d l a	c s ur	me co m	st m	n r m	n r	c ti	va ov	de n c	de c	c c	
,329	.																			Sig. (2-tailed)
,212																				Correlation Coef
,294	,260	.																		Sig. (2-tailed)
,237	,228																			Correlation Coef
,462	,074	,272	.																	Sig. (2-tailed)
,170	,371	-,236																		Correlation Coef
,964	,693	,832	,707	.																Sig. (2-tailed)
,010	,075	,042	,076																	Correlation Coef
,696	,639	,322	,099	,052																Sig. (2-tailed)
-,129	-,141	-,308	,544	,578																Correlation Coef
,343	,806	,796	,512	,554	,360	.														Sig. (2-tailed)
,320	,076	,082	-,213	,178	-,310															Correlation Coef
,166	,311	,673	,574	,074	,614	,018														Sig. (2-tailed)
,433	,287	,123	-,170	,497	-,161	. ,766														Correlation Coef
,197	,851	,378	,601	,098	,258	,344	,048	.												Sig. (2-tailed)
,378	,050	-,242	,148	,434	,330	,284	. ,546													Correlation Coef
,612	,252	,153	,600	,268	,777	,592	,148	,790	.											Sig. (2-tailed)
-,163	-,339	-,438	,163	-,323	,093	,194	-,489	-,084												Correlation Coef
1,000	,260	,696	,602	,521	1,000	,346	,431	,055	,355	.										Sig. (2-tailed)
,000	-,297	-,106	-,147	,167	,000	,280	,216	,494	,287											Correlation Coef
,618	,696	,899	,934	,788	,575	,484	,845	,469	,277	,652	.									Sig. (2-tailed)
,102	-,072	,024	-,016	,048	,160	-,204	,053	,184	-,304	,114										Correlation Coef
,239	,696	,899	,649	,788	,313	,062	,696	,469	,385	,241	,184	.								Sig. (2-tailed)
,240	-,072	,024	,089	-,048	-,289	,544	,105	,184	,243	,296	,230									Correlation Coef
,786	,845	,800	,649	,398	,653	,639	,695	,928	,128	,587	,000	,048	.							Sig. (2-tailed)
,056	,036	,048	,089	,151	,130	-,138	,107	,023	-,426	-,138	,647*	,343*								Correlation Coef
,362	,803	,153	1,000	,488	,813	,367	,598	,922	,023	,845	,001	,146	,001	.						Sig. (2-tailed)
,204	,050	,298	,000	,135	-,073	-,286	,154	,027	-,678*	,053	,656*	,275	,643*							Correlation Coef
,852	,936	,664	,200	,036	,265	,902	,401	,097	,718	,174	,695	,255	,724	,967	.					Sig. (2-tailed)
-,040	-,016	,087	-,263	,394*	,346	,038	,243	,450	-,110	,366	-,071	-,207	-,064	,008						Correlation Coef
,821	,845	,800	,967	,788	,433	,815	,845	1,000	,277	,928	,081	,224	,305	,182	,157	.				Sig. (2-tailed)
,046	-,036	,048	-,008	,048	-,225	-,068	-,053	,000	-,304	,023	,304	,211	,179	,253	-,258					Correlation Coef
,617	,455	,704	,803	,787	,646	,905	,619	,712	,380	,520	,036	,469	,195	,256	,168	,000	.			Sig. (2-tailed)
-,104	-,140	-,074	-,049	,049	-,136	-,036	-,138	-,096	-,250	-,167	,369*	,128	,229	,218	-,255	,781**				Correlation Coef
,618	,907	,643	,901	,939	,433	,640	,558	,856	,277	,928	,111	,224	,382	,210	,169	,000	,000	.		Sig. (2-tailed)
,102	,022	,089	,024	,014	-,225	-,136	-,158	-,046	-,304	-,023	,277	,211	,152	,237	-,251	,894**	,660*			Correlation Coef
,294	,477	,702	,616	,561	1,000	,550	,842	,517	,578	,854	,848	,116	,702	,654	,635	,007	,178	,001	.	Sig. (2-tailed)
,220	,134	,075	,100	,106	,000	-,180	-,056	,171	-,161	,048	,034	,279	,068	,087	-,089	,485*	,243	,601*		Correlation Coef
,751	,907	,736	,097	,004	,177	,484	,281	,237	,743	,103	,324	,149	,063	,182	,875	,305	,401	,470	,319	Sig. (2-tailed)
-,065	-,022	-,064	,324	,516*	,390	,204	,293	,302	,093	,414	,172	,251	,325	,253	,029	,179	,148	,126	,178	Correlation Coef

Correlations based on Kendall-T-b

The statistically significant results of the correlation tests are listed below:

- Statistically significant positive correlation between the quality of concept and the overall quality value, which is based on the quality of the design and the completeness, not on the concept value (see Section 6.1.3).
- Statistically significant positive correlation between quality of concept and quality of design.
- Statistically significant positive correlation between the quality of the design and the completeness of the design.
- Statistically significant positive correlation between mean contentment and the completeness of design. This means the more complete the designs are, the more content the participants feel.
- Statistically significant positive correlation between mean contentment and mean motivation. The more content the participants are with their results, the more motivated they are and/or the other way round.
- Statistically significant positive correlation between mean stress and mean motivation. This means the higher the stress, the higher the motivation or the other way round.
- Statistically significant positive correlation between time needed to finish the concept and the number of guidelines that are applied.
- Statistically significant positive correlation between time needed to finish the concept and the term of study.
- Statistically significant positive correlation between mean motivation and the initial motivation at the beginning of the test.
- Statistically significant positive correlation between mean contentment and the initial motivation at the beginning of the test.
- Statistically significant negative correlation between agreeing that application of the guidelines is additional stress and the initial motivation at the beginning of the test.
- Statistically significant positive correlation between support provided by guideline set and number of guidelines applied.
- Statistically significant positive correlation between support provide by guideline set and agreeing that the guidelines are useful for developing flexible products.

The interpretation of the correlations has to be handled carefully. As there is no theory supporting a direction, it is not clear which is the effect and which the cause. For example, the data shows a correlation between contentment and motivation. Whether the higher motivation led to higher contentment, or higher contentment to higher motivation, or if the two variables are linked in a more complex way cannot be clarified.

It can be reasoned, however, that some participants performed better than others, which is shown by the correlation of quality of the concept and the overall quality value and the correlation between the quality of the design and the completeness. Probably the participants could evaluate their own performance reasonably and thus were more content (correlation between contentment and completeness of the designs).

As explained in Section 6.3.5 there is a statistically significant positive correlation between the initial motivation and the motivation during the whole test. This means that the decline of motivation during the test was similar among the participants. Thus, the ones that started with a higher motivation kept this higher level the whole time.

A negative result of this analysis is the correlation of time needed to finish the concept and the number of guidelines that were applied. This means that applying the new guidelines led to a statistically significant delay of the working progress. Thus, this negative effect of the application has to be well balanced with the assumable positive effects.

6.6 Summary and Discussion

A laboratory study was set up in order to evaluate the newly derived guidelines. In this chapter, the results of the evaluation were presented. The results are summarized in Table 6-24.

Not all research questions and hypotheses could be answered satisfactorily. More research is necessary to clarify these complex issues of developing flexible and robust products in changing environments mainly to benefit already during the development process. Nevertheless, the study already shows benefits of applying the guidelines and developing flexible and robust products for changing environments. These benefits were mainly higher motivation and contentment of the participants working with the guidelines. Moreover, the workload for implementing changes was lower when working with the guidelines, the time needed to finish the concept was lower and while for the without GL group the changes led to a complete refusal this effect did not occur for the with GL group. However, not all positive effects are statistically significant based on strict confidence level of $\alpha=0.05$. The study also discloses some downsides of this approach, for example the higher stress due to the guideline application.

Table 6-24 Overview of outcome of the evaluation of research questions and hypotheses

	question/hypothesis (shortened)	result	conclusion
H0.1	GL do not negatively affect quality of the concepts.	fail to reject	Similar quality of concepts for both groups.
H0.2	GL do not negatively affect quality of the design.	fail to reject	Similar quality of designs for both groups.
H1.1	GL lead to more flexible/robust products.	not tested	Due to the lack of an appropriate tool direct evaluation is impossible.
RQ1	*Does the application of the proposed guideline set lead to more flexible and robust products?*	*Positive effects on the other hypotheses are assumable based on the higher product flexibility/robustness and thus indicate a positive trend here as well. However, further research especially on the measurement of flexibility is strongly proposed.*	
H2.1	Changes can be implemented sooner after occurrence with GL.	no results due to insufficient data	Further research is necessary.
H2.2	Changes can be implemented faster with GL.	rejected	No statistically significant differences in time needed for change implementation between the two groups.
H2.3	Changes have less negative effects on the concept/design with GL.	rejected	No statistically significant differences in effect of changes on concept/design between the two groups.
H2.4	With GL motivation drops less when changes occur.	fail to reject	Motivation is higher and drops less when working with the GL.
H2.5	With GL stress is lower when changes occur.	rejected	Effort is statistically significantly higher when working with the GL.
H2.6	With GL the contentment is higher when changes occur.	mixed results	For some points in time the contentment is statistically significantly higher when working with the GL.
RQ2	*Flexible/robust products help handling changes in the development process?*	*Designing flexible/robust products with GL has positive effects in changing environment, but more research is proposed for more unambiguous statements.*	
H3.1	New GL are easy to understand.	fail to reject	GL are considered to be easy to understand.
H3.2	GL are supportive to the designer.	mixed results	Further research is necessary.
H3.3	GL can be applied in concept and in embodiment design phases.	fail to reject	GL are applied successfully in concept and embodiment design phase.
RQ3	*Is the developed support suitable for developing flexible and robust products?*	*The GL are a suitable tool. The quality of the support and its results have to be researched in detail for more definite statements.*	

The study design is limited; it is based on simple product development models, especially to analyze the effects for H2.1, H2.2, and H2.3. The reality of product development is far more complex. The approaches of working on a design task are diverse. Therefore evaluation and comparison especially of progress, time and completeness is limited and the comparison between the participants is difficult.

Comparisons with other supports, tools and methods were not carried out. Therefore, clear evaluations of H3.2 on the support by the new guidelines cannot be made.

Advantages and disadvantages of laboratory studies are widely discussed (e.g. Blessing & Chakrabarti 2009). Why a laboratory setting was chosen instead of industrial application has been already discussed. Carrying out the study with engineering design students (see Section 5.2.6) instead of experienced developers, did not lead to any obvious negative aspects. The design task (see Section 5.2.4), the training on the guidelines (see Section 5.2.5), the presented changes and additions, the test design with concept and embodiment design phase (see Section 5.2.2), and the whole study design (see Section 5.2) seem all to have reasonably been chosen, despite the low number of correctly filled questionnaires. This was due to the rather limited number of participants as well as due to low rate of correctly filled questionnaires. Future studies should take this into account and be optimized towards easier and more reliable data collection.

The revised Impact Model illustrates the situation of research problem of developing flexible and robust products with help of the guidelines including the findings of the presented study (see Figure 6-30)

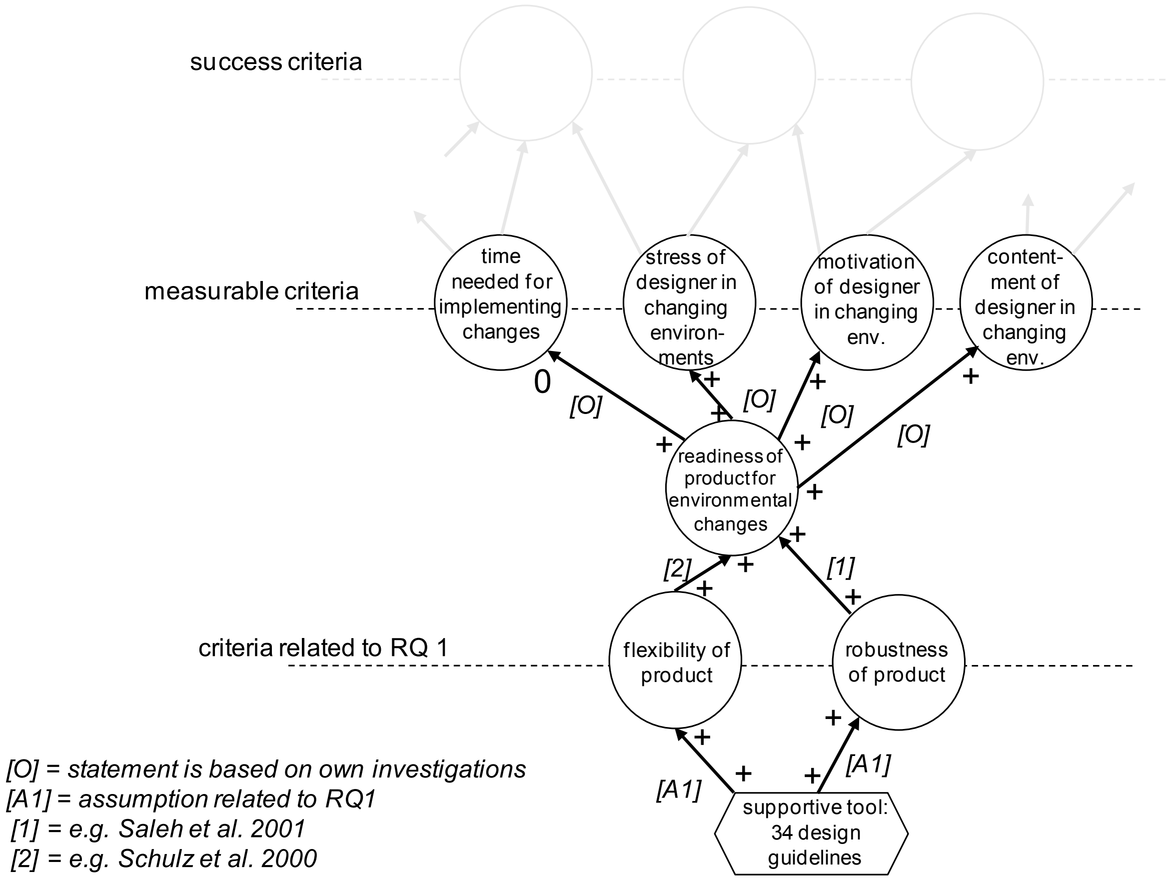

Figure 6-30 Revised Impact Model (excerpt) based on Initial Impact Model in Figure 6-7

The model shows that the assumptions related to RQ2, which were shown in the Initial Impact Model, are now replaced by statements based on the investigations made in this work. Two of the assumptions related to the link between readiness of product for environmental changes and motivation and contentment of the designer could be supported with the data.

In contrast the higher readiness of the product does not lead to a reduced time needed to implement changes; the data suggests that there is hardly an effect between these two factors. The values on the link between readiness of the product and stress were assumed incorrect. The study shows that the values on the link between product readiness and stress have to be inverted: the higher readiness (the application of the guidelines, respectively) led to higher stress in the study.

The assumptions related to RQ1 (more flexible and robust products due to guideline application?) could not be replaced with the findings of the study. They remain assumptions, but the assumptions are now based on more profound data.

However, transfer of the findings to real, industrial based development projects still lies ahead.

7 CONCLUSION AND FUTURE WORK

In this work developing flexible and robust products was discussed as an approach in product development to handle uncertainty and changes in the environment, especially during the development of the product. New definitions for flexible and robust products were derived. Various approaches, which support the development of flexible and robust products, were analyzed. Based on a literature study a new support of 34 design guidelines was derived and presented. The support was applied in a laboratory study as well as in a participative observation development project. The results of the laboratory study were presented in Chapter 6. This chapter summarizes the results and provides recommendations for future research and for product development practice.

7.1 Summary

The practical aims of this research were to give one possible solution to the problem of developing products in uncertain and changing environments and to provide a support for the development of flexible and robust products to ease handling of uncertain and changing requirements. This problem-triggered improvement process was carried out in a classical engineering and solution-focused way. The scientific aim was to understand the phenomenon of flexibility in product development and to find out if product flexibility is a useful way to cope with changing environments and to answer the formulated research questions and evaluate the hypotheses. The approach taken is illustrated in Figure 7-1.

	Research Clarification	Descriptive Study I	Prescriptive Study	Descriptive Study II
Goal	• Define scope • Define Research Questions • Determine measurement criteria • "What is the problem?"	• Gain understanding • Check usefulness of flexibility • Derive ideas for support	• Develop supportive tool	• Evaluate tool
Activities	• Identify criteria • Participate in product development project	• Analyze literature • Analyze existing approaches • Cluster existing approaches	• Develop supportive tool	• Develop study for tool evaluation • Carry out study • Analyze results
Results	• Scope • Motivation and background information • Definition of Key Questions	• Knowledge of approaches for coping with changing environments	• 34 Design guidelines for the development of flexible and robust products	• Study design •Questionnaires for study • Findings from study • Conclusions
Method	• Literature study • Action Research	• Literature study • Action Research • Pretests	• Literature study • Action Research • Pretests	• Empirical Study • Statistical analysis
Chapter	Chapter 1	Chapter 2 and 3	Chapter 4	Chapter 5 and 6

Figure 7-1 Approach based on Design Research Methodology for development and evaluation of guidelines for the development of products for changing environments

The figure shows that all four stages of the DRM have been carried out. For the Research Clarification a literature study and Action Research have been applied in order to define the scope and the key question of this work. In order to gain a deeper knowledge about the approaches for coping with changing environment a literature study, Action Research and pretests have been carried out. They form the Descriptive Study I. A support for product developers for developing flexible and robust products was generated in the Prescriptive Study. The support consists of 34 guidelines, which can be found in the appendix of this work. In order to evaluate the support the Descriptive Study II was carried out. The study itself and the results are presented in detail in Chapters 5 and 6.

7.2 Discussion, Conclusions & Contributions

The advantages and disadvantages of applying flexibility and robustness in product development processes and developing flexible products were discussed in Chapter 2. It can be concluded that flexibility, either on the process side or on the product side, has a lot of potential to successfully develop technical products in changing environments. Various industrial applications of product flexibility or robustness in one of their various forms, have retrospectively led to positive outcome. The proactive application of flexibility and robustness in this work has shown less explicit results: Applying flexibility and robustness in the product by applying the newly derived design guidelines in order to handle changes during the development process did not only have the expected positive effects on the process and the product developers.

The formulated fundamental conditions of the guideline application were: H0.1: Applying the newly generated design guidelines does not negatively affect the quality of the concept and H0.2: Applying the newly generated design guidelines does not negatively affect the quality of the design. Based on the findings of the study there was not enough evidence to reject these hypotheses, which therefore are retained. The application of the guidelines in product development projects does neither effect the quality of the concept nor or the design in a negative way.

The results from the laboratory study show that working with the guideline set led to statistically significant higher stress at some points in time during the test. The stress was higher, when working with the guidelines than when working without them. On the positive side, the application of the guidelines did lead to statistically significant higher motivation and contentment with the own work (at some points in time during the test).

Moreover, the application of the guidelines did neither affect the results of the generated concepts nor of the designs in a negative way. When working with the guidelines the results were slightly better; but the differences are not statistically significant.

The hypotheses of implementing changes sooner and faster when developing flexible and robust products could not be statistically confirmed.

Whether the application of the new guidelines leads to more flexible and robust products, which are better prepared to handle changes, could not be answered directly. As already explained in Section 6.2.2 the answer can only be given in an argumentative way based on the other findings of the study. The data supports the assumption that applying the guidelines in product development projects leads to the aimed results of higher product flexibility and robustness.

Long term effects of product flexibility are not analyzed within the study. The advantages of (product) flexibility and robustness are higher in longer lasting development projects, as indicated by Figure 2-2, which illustrates that the effort for implementing changes progressively increases over time and development progress. Moreover, the positive effects of product flexibility for follow up products, as illustrated in Figure 2-21, had to be excluded from this research. Long term effects of applying the guidelines could also not be analyzed within this study. Hence, it can only be assumed that the additional stress, caused by the guidelines, will decline with more routine due to frequent application.

The approach taken, to implement product flexibility by supporting the development process with new design guidelines, seems promising. The idea has earned positive feedback in various scientific discussions and the laboratory study has shown results with good prospects. The understanding of the new guidelines was rated high, even though the teaching, practicing and application of the guidelines was relatively short. A simple support of illustrated design guidelines still seems to be a suitable support for a complex task as developing products in changing environments. The participants agreed to an extent with the idea behind the guideline that developing flexible and or robust products are useful to handle changes during the development process. However, it was not conveyed to the participants that the use of the guidelines was supposed to better prepare them to handle changes. Nevertheless, positive effects on motivation and contentment could be observed.

Overall, the positive effects of the guideline application are less distinctive than expected. Implementing flexibility in a product in order to derive benefits for the process is challenging. Nonetheless, the study described in this work has shown potential for flexible and robust product design in changing environments.

The main contribution of this work to engineering design science and practice is a consolidation of ideas, various product development approaches, which are considered to be useful for the development of products in changing environments. The consolidation of these approaches is realized in 34 new, illustrated guidelines. It is concluded that classical engineering design guidelines are still adequate to support modern product development projects. Moreover, the basic idea of proactively implementing product flexibility and robustness was evaluated in a laboratory setting and thus dissociated from over optimistic and subjective descriptions of successful industrial application. Further research and industrial application should build on this basis.

It can be concluded that the newly generated design guidelines can and should be further researched (see Section 7.3) as well as carefully implemented in industrial practice (see Section 7.4) in order to take advantage of the whole potential of flexibility in product development.

7.3 Suggestions for Future Research

The results of this study are less significant than expected; not all hypotheses could be evaluated and not all research questions could be satisfactorily answered. Hence, more research is necessary. First of all it is proposed to repeat exactly this study with a greater number of participants, as the small number of samples is one major reason for the unsatisfactory evaluations of the hypotheses and answers on the research questions. Therefore the study design is clearly described and the design task as well as the questionnaires and the design guidelines are added in the appendix. Repeating this study with a greater sample size will hopefully lead to more significant results and definite evaluations on the hypotheses.

Furthermore this study can be understood as an initial study of the approach of proactively developing product flexibility and robustness to handle changes during a development project. The analysis of the effects of applying the new design guidelines in long term development projects is simplified to a three hour laboratory setting. Therefore it is strongly proposed to evaluate the design guidelines and the effects of their application in longer projects. These could be carried out in an academic context as well as in industrial contexts.

Moreover, it should be analyzed, why working with the guidelines has positive effects on the motivation as well as on the contentment with the own work. This is especially interesting, as positive effects where identified already before changes were presented to the developers, thus, before beneficial effects from the guideline application may emerge according to the formulated theory.

The guidelines used within this study are a consolidation of various approaches and not completely free of contradictions. Hence, more research to specify the guidelines and the approach for specific development projects (branches, duration, product type, production volume, etc.) is proposed.

Figure 7-2 below is a repetition of Figure 1-2, which was used to explain the scope of this research. It furthermore illustrates various areas of possible further research.

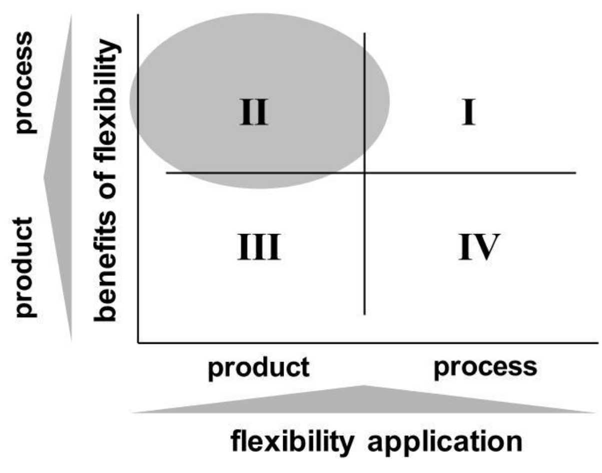

Figure 7-2 Research areas for future work on flexibility in product development

Process flexibility is described as fundamental in various references. Sector I of Figure 7-2 is about increasing the flexibility of product development processes in order to directly benefit from the flexibility. Even though much research has been carried out in this area it is definitely worth further research as its potential and impact on the whole product development has already shown promising improvements.

Sector II was the focus of this work. Product flexibility is enhanced in order to derive the benefits of flexibility already during the development process.

Sector III is about implementing product flexibility in the product design in order to achieve a more flexible product. Further research within this area could focus on measuring product flexibility, to answer research question RQ1 of this study. Moreover, product flexibility is of high value to the customer. Enhancing this value legitimates further research in this area.

Sector IV can be explained as enhancing process flexibility in order to develop more flexible products. This seems to be challenging; no references can be found, which describe an attempt in this direction. Besides the general benefits of the process flexibility and product flexibility at the same time it is difficult to imagine a reasonable example of enhancing process flexibility especially to increase the flexibility of the product. However, research within this area might be useful before finally judging and neglecting this approach.

Until now, the evaluation of the guidelines and the approach of developing flexible products for changing environments are purely academic. Further analyses in practical applications are necessary for the evaluation of the usefulness of both the approach and the guidelines in industrial practice.

7.4 Recommendations for Product Development

In this work, a new support is presented, which aims at helping to handle changes during the development of technical products. However, negative effects, e.g. a decline in motivation, occur even when applying the guidelines. Therefore, in practical development projects changes should be avoided. For most successful product development Gebhard (1997) proposed a dynamic yet smooth process without turbulences so that developers feel more secure and motivated and planning reliability is enhanced. This, however, is almost impossible in real projects. Therefore, here it is recommended to enhance the flexibility of product development, of the methods and methodologies, the tools, the process, the products and the people.

More than ten years ago Thomke (1997b) concluded “we have seen how important design flexibility can be for product development success, particularly in uncertain and unstable environments, and therefore I propose that flexibility should play an integral role in the design process.” There is still much work ahead to integrate flexibility in product development practice. Therefore, this work proposes to consider flexibility on the process side as well as on the product side for industrial product development projects. The newly derived design guidelines can be used as a support for this approach. These guidelines do not only help to develop products with a specific design for changing environments, but also remind the product developers of the importance of flexibility and robustness in the development context.

It is important to create a mindset of flexibility in product development in general. By doing so, flexibility is not only deeply integrated in product development, but changes during (and after) the development phase can be interpreted as possibilities rather than as threats, as people involved in the product development process are better prepared to handle such changes. According to Smith (2007) the “people are most important for changes.“

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APPENDIX

A1 Analyzed Development Approaches

Table A1 - 1 Application and Support – literature overview

Approach	Main Benefit		Main Goal					Basic Idea					Background						Support								Possible Use/Application						Target Area / Domain		
	company	customer	create flexibility for customer	match customers' requirements with diverse products	match customers' requirements with single product	reduce costs/time	other	optimize production/manufacturing	enhance product flexibility	create variety/range of products	adjust product to requirements	other	academic (not applied)	aerospace	automotive	consumer goods	software and IT	other	awareness	understanding	strategy	method/methodology	calculation (-tool)	computer based tool	guidelines	other	strategy (company)	product portfolio	product planning	conceptual design	embodiment design	other	production/manufacturing	development	other
Optimized Product																																			
Chakrabarti 2001	●	○					●	○					○							○									○	○	○			○	
Laporte & LeTallec 2002	●						○	○					○										●	○						○	●			●	
Mohandas and Sandgren 1989	●						●	●				○	○										●	○						○	●			●	○
Pahl et al. 2007	●	○				○	○	○				○	○					○				○				○			○	○	○			○	
Ulrich & Eppinger 1995	●	○				○	○	○				○	○					○				○				○			○	○	○			○	
Robust Product																																			
Jiang & Allada 2001	●				○		○				○	○	●						○			○	○						○	○		○		○	
Saleh et al. 2001		●			○	○	○				●			●					●	●			○				○		○					○	○
Taguchi 1987	●						●	●				○	●	○							○	●					○		○	○		○	●		
Product Modularization																																			
Andersson & Sellgren 2002	●						○				○	○	●									○		○					○	○				●	
Baldwin & Clark 1997	●			●		○			○	○	○		●						○	●	○						○		○						○
Blackenfelt 2001	●			○	○	○					○	○							○			●			○				●	●				●	
Cebon et al. 2002	●				●				○		○		●						○	○	○	○	○	○					○					○	○
Erixon 1998	●			○	○	○	○		○	○	○		●									●			○				●	●				●	
Hölttä & Otto 2005	●				○	○	○		○		○	○	●					○				●							●	●				●	
Höltta & Salonen 2003	●			○	○	○	○		○	○	○		●									●							●	●				●	
Hölttä et al. 2005	●			○	○	○	○				○		●							●		○							●	●				○	
Ishii & Yang 2003	●					○	○				○	○	●		●					○		○							○	○				○	
Lehtonen et al. 2003	●					○	○		○	○	○	○	●					○				●							○					●	
Marshall & Leaney 1999	●						○					○	●						○	○		○							○					○	
Mikkola & Gassmann 2003	●			●					○	○	○		●					○				●	○						○	○				○	
Nepal et al. 2006	●			○	○	○					○	○	●									●	●	●					○	○				○	
Persson & Ahlstrom 2006	●												●		●				○	○	○						○	○							○
Sosa et al. 2000	●						○					○	●	●								○	●						○	○				●	
Van Wie et al. 2001	●					○	○		○	○	○	○	●			○						●						○	○	○				●	

● = matches perfectly

○ = matches to some extend

Table A1 - 1 continuation

Approach	Main Benefit		Main Goal					Basic Idea					Background						Support								Possible Use/Application						Target Area / Domain		
	company	customer	create flexibility for customer	match customers' requirements with diverse products	match customers' requirements with single product	reduce costs/time	other	optimize production/manufacturing	enhance product flexibility	create variety/range of products	adjust product to requirements	other	academic (not applied)	aerospace	automotive	consumer goods	software and IT	other	awareness	understanding	strategy	method/methodology	calculation (-tool)	computer based tool	guidelines	other	strategy (company)	product portfolio	product planning	conceptual design	embodiment design	other	production/manufacturing	development	other
Product Flexibilisation																																			
Fricke & Schulz 2005	●		○	○	●	○	○		●	○	●		●		●							●			●				●	●				●	
Haberfellner & de Weck 2005	●		○	○	○		○		○	○	○	○	●	○					○	●		○							○	○				○	○
Iansiti 1995	●						●					●	●						○	○									○	○		○		○	○
Jordan et al. 2005	●		○		○				●		●		●	●					○	●	○								○	○		○		○	○
Nilchiani & Hastings 2004	●	●	○		○				○		○		●	●						○	○		●						○	○		●		●	
Nilchiani et al. 2005	●	●	○		○				○		○		●	●						○	○		●						○	○		●		●	○
Palani Rajan et al. 2003	●		●	○	●				●		○		●			○			○	○		○	○		●			○	●	●				●	
Palani Rajan et al. 2005	●		●	○	●				●		○		●			○			○	○		○	○		●			○	●	●				●	
Reik et al. 2005	●					●		●					●					○	○	○									○			○	○	○	○
Roser and Kazmer 1999	●				●		○		○		○	○	●									○	○				○		○					○	○
Saleh et al. 2003	●						●		○	○	○	○	●	●					○	●												●		○	○
Saleh et al. 2008	●		○	○	○				○	○	○		●						○	○	○						○	○	○	○				○	○
Sanchez & Mahoney 1996	●		○	○	○	○			○	○	○		●						○	○	○	○			○		○	○	○	○				○	○
Schulz & Fricke 1999	●		○	○	○				●	○	○		●							●		○			●			○	○	○				●	
Schulz et al. 2000	●		○	○	○				●	○	○		●							●		○			●			○	○	○				●	
Smith 2007	●		○	○	○	○	○	○	○	○	○	○	●					○	○	○	○	○			○		○	○	○				○	○	○
Thomke & Reinertsen 1998	●		○		○		○		○		○	○	●					○	○	○	○	○			○		○	○	○					○	○
Thomke 1997a	●		○		○		○		○		○	○	●					○	○	○	○	○					○	○	○					○	○
Thomke 1997b	●		○		○		○		○		○	○	●						○	○	○				○		○	○	○					○	○
Van Wie 2002	●	○	○	○	○				●		●		●									●			●				○	●	○			●	
Platform Based Approaches																																			
Berglund & Claesson 2005	●			●		○				●			●		○					●							○	○	○	○				○	○
Caffrey et al. 2002	●			●		○				●				●						○					●				○	○	○			●	
Dana 2003	○			○		○		○		○			●										●						○			○	○	○	
Gonzalez-Zugasti et al. 2000	●			●		○				●	○		●	●								●		○					○	○				○	
Gonzalez-Zugasti et al. 2001	●			●		○				●			●							○		○	○						○	○				○	
Gupta & Benjaafar 2004	●			●						●	○		●										●									○	○		○
Halman et al. 2003	●			○		○				○		○	●					○		●									○	○				○	
Hölttä-Otto 2005	●			○		○				○			●							●		●	○		○				○	○				○	
Lehtonen et al. 2005	●			●			○			●			●						○	●									○			○			○
Mortensen et al. 2005	●			●						●			●							●		○					○		○					○	○
Muffatto & Roveda 2000	●			○		○				○		○	●			○		○		●									○	○				○	
Muffatto & Roveda 2002	●			○		○				○		○	●							●									○	○				○	
Pulkkinen et al. 2003	●			●		○				●			●				○	○	●	●							○	○	○					○	○
Robertson & Ulrich 1998	●			●		○		○		●			●		○					○	○	○							○					○	○
Simpson & Mistree 1999	●			●		○				●			●					○			○	●					○	○	○					○	○
Simpson 2003	●			●			○			○			●						○	●							○	○	○					○	○
Simpson et al. 2001	●			●						●			●			○		●		○	○	●					○	○	○					○	○
Suh 2005	●			●		○				●			●		○							●							○	○				●	○
Sundgren 1999	●			●				○		○			●	○	○	○	○	○		○	○						○		○						○
Van Wie et al. 2004	●			○		○				○		○	●					○		●									○	○				○	
Veenstra et al. 2006	●			●		○				●	○		●					●		○		○	○						○	○					○
Yang et al. 2004	●			●						●			●			○				○		●						○	○					○	○

● = matches perfectly
○ = matches to some extend

Table A1 - 1 continuation

Approach	Main Benefit		Main Goal					Basic Idea					Background						Support								Possible Use/Application						Target Area / Domain		
	company	customer	create flexibility for customer	match customers' requirements with diverse products	match customers' requirements with single product	reduce costs/time	other	optimize production/manufacturing	enhance product flexibility	create variety/range of products	adjust product to requirements	other	academic (not applied)	aerospace	automotive	consumer goods	software and IT	other	awareness	understanding	strategy	method/methodology	calculation (-tool)	computer based tool	guidelines	other	strategy (company)	product portfolio	product planning	conceptual design	embodiment design	other	production/manufacturing	development	other
Architecture Oriented Approaches																																			
de Neuville 2003	●				○		○		○		○		●					○		○							○	○	○						○
Engel & Browning 2006	●				○		○		○		○		●					○				○	○					○	○					○	○
Fixson 2005	●				○	○	○					○	●									●							○			○	○	○	○
Harlou 2006	●			●		○		○		●			●			○		○	○	○		○			○			○	○	○			○	●	○
Larses 2005	●				○	○					○		●		●							●	●	●				○	○	○				○	
Maier 1996	●				○	○					○		●	○				○		○		○							○					○	○
Malmström & Malmqvist 1998	●				○	○					○		●	●								●							○					○	
Ulrich 1995a	●				○	○					○		●						●	○							○	○	○	○				○	○
Size Ranges, Product Family and Variety																																			
Chakravarty & Balakrishnan 2001	●			●						●			●									○	●					○							○
Erens 1996	●			●						●			●			○		○	●	●						○		○	○					○	
Fisher et al. 1999	●					●		○				○			●					○		○	○					○	○			○	○	○	
Fujita 2000	●			●						●				●									●					●	○					●	○
Jiao et al. 2006	●			○		○				●								●					●									●			●
Martin & Ishii 2002	●			●	○				●	●			●					○				●	●		●			●	●	○	○			●	○
Meyer & Utterback 1993	●			●						●			●						●	●								○	○					○	○
Pulkkinen & Bongulielmi 2004	●			●						●			●						●	●								○	○					○	○
Pulkkinen & Bongulielminen 2004	●			●						●			●						○	●								○	○					○	○
Puls et al. 2002	●			●						●			○		○								●					●	○					○	○
Sanderson & Utzumeri 1995	●			●		●				●			○			●			○	○	○						○	○	○				○	○	○
Mass Customization																																			
Calvo et al. 2006	●			○		○		●					●					○				○										○	●		
Da Silveira et al. 2001	●			●	○					●			●						●	●								○	○						○
Dörflinger & Marxt 2001	●			●	○					●	○		○					○	○	○	○						○	○	○					○	○
Jiao & Tseng 2004	●			●	○					●	○		●				●						●	●				○	○	○				○	○
Krishnapillai & Zeid 2006	●			●	○					●	○		●							○			●					○	○					○	○
Piller 2004	●			●	○					●		○	●						○	●							●	○	●					○	●
Pine 1999	●			●	○					●					○	○		○	●	●	●	○					●	○	●						●
Miscellaneous Approaches																																			
Andreasen et al. 1988	●					●						●	●					●							●					●	●			●	
Bein et al. 2005	○	○	○		○		○		○		○		●					○	○							○			○	○		○		○	○
Blessing & Schmidt-Kretschmer 2004	○	○	●		○		○		●		●		●					○	○			○				○			○	○		○		○	○
Bode 1984	●					○	○	○					○					●				○			●					●	●			●	
Dix 2007		○	○						○		○		○						○						○				○	○				○	
Dix 2008		○	○						○		○		○						○						○				○	○				○	
Hashemian 2005	●	●	●		●				●		●		●									●			●				●	●				●	
Moran 2002		○	○						○		○		○						○										○	○				○	
Newman et al. 2002		○	○						○		○		○						○						○				○	○				○	
Pahl et al. 2007 adaptronics	○	○	○		○		○		○		○		○					○	○							○						○		○	○
Pahl et al. 2007 multi-life-products	○	○	●		○		○		●		●		●					○	○			○				○			○	○		○		○	○
Rampersad 1996	●					●						●	●					●							●					●	●			●	

● = matches perfectly

○ = matches to some extend

A2 Product Development Guidelines for Flexible Products

The developer fixes the characteristics of the product during the product development process (PDP) by which the later properties of the product arise. One these properties is the flexibility of the product. Regardless of the motives for the desired flexibility different development guidelines can be defined, which should support the product development process.

Following a list of 34 development guidelines is presented, which supports the systematic development of flexible products.

Flexibility is understood as a measure of the adaptability to changed demands and environments. The higher the time and expenses needed for the implementing changes in the product, the product has to be considered less flexible. And vice versa: the less time and expenses are needed to implement changes in the product, it is considered the more flexible. If a product despite of changing requirements does not need to adapted, one speaks of a robust product.

The introduced guidelines aim at supporting the development of more flexible as well as at the development of more robust products; due to the high correlation no differentiation between flexible and robust is made for the particular guideline.

The list with 34 directives does not claim to completeness. It is divided after six higher principles for the development of flexible products:

- Decoupling and Modularization (MD)
- Inherent flexibility (IF)
- Easy (dis-)assembly (DA)
- Standardization (ST)
- Extended use (EU)
- Over-Engineering (OE).

Table A2 - 1 Mapping derived guidelines with references

Guidelines / Approach	Modularization									Inherent Flexibility						DA		ST				Extended Use						Over-Engineering						
	MD.1	MD.2	MD.3	MD.4	MD.5	MD.6	MD.7	MD.8	MD.9	IF.1	IF.2	IF.3	IF.4	IF.5	IF.6	DA.1	DA.2	ST.1	ST.2	ST.3	ST.4	EU.1	EU.2	EU.3	EU.4	EU.5	EU.6	OE.1	OE.2	OE.3	OE.4	OE.5	OE.6	OE.7
Optimized Product																																		
Pahl et al. 2007	○		○	○	○											○	○	○	○	○														
Ulrich & Eppinger 1995	○		○	○	○											○	○	○	○	○														
Robust Product																																		
Jiang & Allada 2001	○	○	○	○	○	○	○	○											○	○														
Saleh et al. 2001																						○	○	○	○	○	○	○	○	○				
Taguchi 1987																							○											
Product Modularization																																		
Blackenfelt 2001	●	●	●	●	●	●												●	●	○	●							●						
Baldwin & Clark 1997	○	○	○																○	○														
Hölttä & Otto 2005	○	○	○	○														○	○	○	○													
Höltta & Salonen 2003	○	○	○	○																														
Hölttä et al. 2005	○	○	○	○																														
Product Flexibilisation																																		
Engel & Browning 2006												○		○	○	○	○	○		○														
Fricke & Schulz 2005	●	●				●		●		●	●	●						●		●		●						●	●	●	●	●	●	●
Nilchiani et al. 2005																						○	○	○	○	○	○	○	○	○	○	○	○	○
Palani Rajan et al. 2003	●	●	●	●		●												●		●												●	●	●
Palani Rajan et al. 2005	●	●	●	●		●												●		●									●		●	●	●	●
Sanchez & Mahoney 1996	○	○	○	○	○	○			○									○	○	○	○													
Schulz & Fricke 1999	●	●				●		●		●	●	●						●		●								●	●	●	●	●	●	●
Schulz et al. 2000	●	●				●		●		●	●	●						●		●		●						●	●	●	●	●	●	●
Smith 2007	●	●	●	●	●	●	●	●	○													○	○	○	○	○	○							
Thomke & Reinertsen 1998			●	●		●																												
Van Wie 2002	●	●	●	●		●												●		●												●	●	●
Platform Based Approaches																																		
Caffrey et al. 2002	●	●	●	●	●	●	●												●	●	●		●											
Harlou 2006			●	●		●												●		○														
Hölttä-Otto 2005			●	●																														
Robertson & Ulrich 1998																	○					○												
Sundgren 1999																									○						○			
Architecture Oriented Approaches																																		
Harlou 2006			●	●		●												●		●														
Ulrich 1995a	●	○	●	○	○										○	○	○	●	●	○								○						
Size Ranges, Product Family and Variety																																		
Fisher et al. 1999																	○				○													
Ishii & Martin 2000	●		●	●		●		●										●														●	●	●
Martin & Ishii 2002	●	●	●	○		○		●																					●			○	○	○
Pulkkinen & Bongulielminen 2004	○		○										○								○													
Mass Customization																																		
Dörflinger & Marxt 2001			●												●			●	●	●	●													
Piller 2004			○																															
Pine 1999	○		●		○																													
Miscellaneous Approaches																																		
Andreasen et al. 1988												○				●	●																	
Dix 2007																		○	○	○														
Dix 2008																		○	○	○														
Dove 1999	○	○		○		○											○	○	○	○										●				
Habraken 1980			○	○														○	○	○														
Hashemian 2005	●		●	●		●						●			●	●		●		●		●						●						
Moran 2002																													○					
Pahl et al. 2007 - adaptronics												●																						
Pahl et al. 2007 - multi-life										●	●				●					●		●						●	●	●	●	●	●	●
Rampersad 1996	○		●		○											○		●	●	●	●				●									

● = guideline derived

○ = guideline idea recognizable

all references with no relation to the derived guidelines excluded

Table A2 - 2 Design guidelines Decoupling and Modularization (MD)

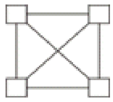
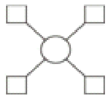
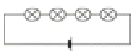
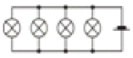
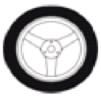
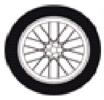
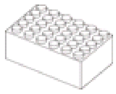
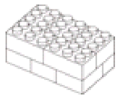
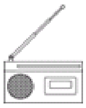
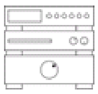
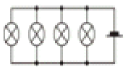
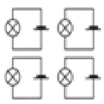
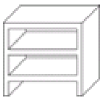
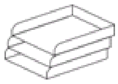
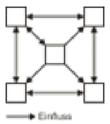
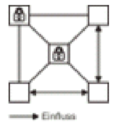
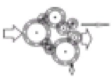
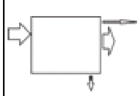
Modularisation and Decoupling (MD)				
#	***guideline***	***not flexible***	***flexible***	***explanation***
MD.1	Minimize internal connections. Use bus systems.			Minimizing the internal connections and making use of bus systems allows easy exchange of product parts during the whole life cycle. The less a part or a module is connected with other parts of the product the less the exchange or change of this part affects the rest of the product negatively. This way later changes can be implemented easier.
MD.2	Reduce internal dependencies.			Reducing product internal dependencies not only assures that when some components break down the product remains its functionality. Moreover, the single components can be changed, replaced or upgraded easily without influencing the whole product.
MD.3	Subdivide the product in modules. Use differential instead of integral design.			Subdividing the product in modules and making use of differential design instead of integral design allow easy replacement of parts. Occurring external changes do not necessarily cause a complete redesign of the original design. Moreover, the modular parts can be used for other products as well.
MD.4	Increase the number of modules.			A product should be divided in a reasonable number of modules and parts if possible. This way a later exchange of single parts and modules is possible and maintenance is eased. Later changes less often effect the whole product; complete redesign is less likely. Role of thumb: the number of modules is about the square root of the number of parts of the whole product.
MD.5	Modularize the product by its functions.			When dividing the product into modules define these by the functions. Integrating (main-) functions in one module leads to a reduced coupling and dependency and thus (ex-) changeability. Function based modules are more likely to be used in other products.
MD.6	Plan autonomous modules.			The dependency of the modules among each other should be reduced so the single modules can be used independently from the others. This way the risk of complete product failure in case of the breakdown of a single module is reduced. The modules can be (ex-) changed easier to adapt them to new environmental conditions. Moreover the use of the modules in other products is eased.
MD.7	Allow up-scaling by connecting multiple modules.			Modules should be interchangeable. Up-scaling by combining identical modules should be possible to realise different product configurations.
MD.8	Block and freeze parts, assembly groups and modules if possible.			The interfaces and main geometrical dimensions of the product should be determined as early as possible and not be changed throughout the process. This way interferences due to changes in the system are minimized. Changes on single components cause less adaption and redesign on the whole system.
MD.9	Make use of the black box approach, first plan input and output, then internal processes.			Input and output parameters and the main geometrical dimensions of the product should be determined before internal mechanisms are detailed. By defining interfaces early, a flexible working style and parallel work on different parts and modules is eased without putting too much effort in the detail design. Later changes can be implemented within a black box without negatively effecting other parts of the product.

Table A2 - 3 Design guidelines Inherent Flexibility (IF)

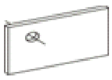
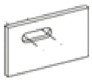
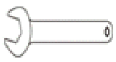
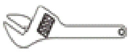
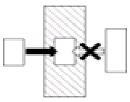
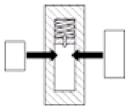
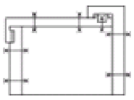
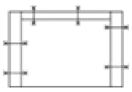
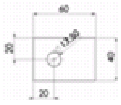
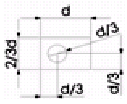
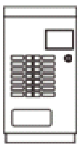
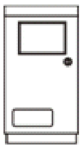
Inherent Flexibility (IF)				
#	*guideline*	*not flexible*	*flexible*	*explanation*
IF.1	Use flexible and change tolerant design features and machine elements.			Design features, for example boreholes, should be designed such that later changes in the configuration can be implemented with little effort. This can for example be realized by making use of slot holes or over-sized holes. This way the part or product does not necessarily have to be changed, when later requirements slightly differ or demand adjusting.
IF.2	Create universal designs.			When the possibility of adjusting the product (e.g. on height, width, angles, etc.) is implemented from the beginning the product can be used in a more universal way and for different applications. Thus the number of necessary single products is reduced, while the range of use and possible users is extended.
IF.3	Use self-adjusting and self-healing designs if possible.			When design features and parts are designed in a way that they are self-adjusting and self-healing, changes can be implemented in the fielded product easier, because adjusting and adapting effort is reduced. The self-adjusting and self-healing designs can for example be realized by specific designs and by making use of material properties.
IF.4	Allow flexible assembly order.			The flexibility of the assembly process can be increased by reducing the process-related dependencies. The single parts and modules can be exchanged later with less effort. Changes on single components do not necessarily affect the whole product and can be implemented with low effort. Moreover maintenance is eased due to simplified assembly.
IF.5	Use parametric design.			Absolute dimensioning should be replaced by parametric values. Later changes can be realized with less effort and in less time. Moreover size ranges and individualized product sizes can be easily realized.
IF.6	Implement software instead of hardware solutions.			If possible replace hardware by software solutions or combined solutions; in general software solutions are more flexible. Software is in most cases easier to change and extend. Moreover, software enables remote maintenance and adaption.

Table A2 - 4 Design guidelines Easy (Dis-) Assembly (DA)

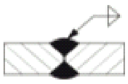
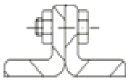
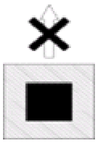
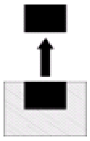
Easy (Dis-)Assembly (DA)				
#	*guideline*	*not flexible*	*flexible*	*explanation*
DA.1	Plan explicit fasteners and consider disconnecting from the beginning.			In order to enhance product flexibility inseparable fasteners should be avoided. Explicitly defined fasteners and disconnecting mechanisms ease the changeability of single parts and modules. Moreover, new products can be realized by combining the parts and modules in new configurations. Early planning of fasteners eases the implementation of change in the later phases of the product life, as usually a (partly) disassembly of the product is necessary for exchange process.
DA.2	Place fast wearing parts and replacement parts at the outside of the product.			Exchangeable and fast wearing parts should be placed such that access is easy. This eases maintenance and reduces change effort, as the components can be reached easier, avoiding complex disassembly work.

Table A2 - 5 Design guidelines Standardization (ST)

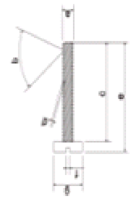
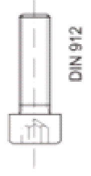
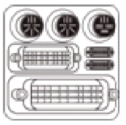
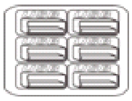
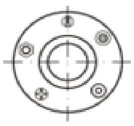
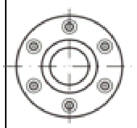
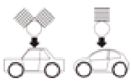
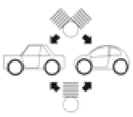
Standardization (ST)				
#	*guideline*	*not flexible*	*flexible*	*explanation*
ST.1	Use standard machine elements and standard parts. Set own standards.			Using standard machine elements and defining company standards for parts and modules eases the exchange of parts and modules, if the other products are based on the same standards. Later upgrades are eased. Development costs can be minimized due to multiple use of modules and products. The (dis-) assembly procedure is eased, if standard machine elements are used; no special tools are needed to implement changes on fielded product.
ST.2	Define standard interfaces (between the modules).			Defining a limited number of standardized interfaces, which fulfill various functions, enhances the possibility of using identical parts and modules for other products. When other products make use of the same interfaces interchange ability is increased. The single parts and modules can be used in a more flexible way.
ST.3	Define a limited number of interfaces and interface variants.			Interfaces with identical functions should be designed identical. When the number of different interface variants is reduced the reduced number of fasteners eases the assembly process. (Ex-) changing of single parts and modules is eased and the likelihood of redesigning a part or module and the interfaces is reduced.
ST.4	Design modules such that they can be used for other products as well.			Modules should be designed in a way, that they are not exclusively usable for one product. Less specified modules ease interchange ability between various products. Interfaces, form and assembly should be designed in a simple way.

Table A2 - 6 Design guidelines Extended Use (EU)

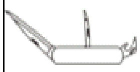
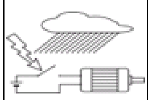
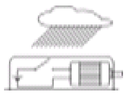
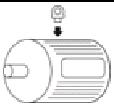
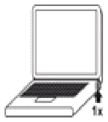
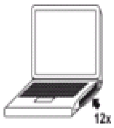
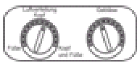
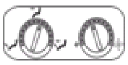
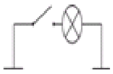
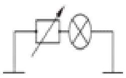
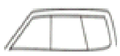
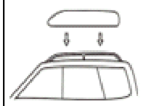
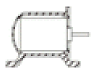
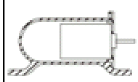
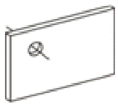
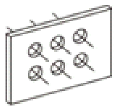
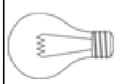
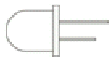
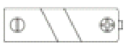
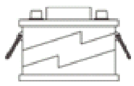
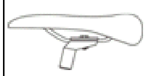
Extended Use (EU)				
#	***guideline***	***not flexible***	***flexible***	***explanation***
EU.1	Plan additional functions and configurations from the beginning.			Integrating useful additional functions enhances functionality of the product and the possible areas of application of the product. When changes in the environment lead to new product requirements there is the possibility that these are already implemented in the product and it does not have to be redesigned or adapted.
EU.2	Design parts to be used in various conditions and environments.			Already in the planning phase different environments for product application should be considered, such as a wide range of temperature, pressure, humidity, etc. Materials and design can be chosen to cope with all these environments. Furthermore, product robustness is enhanced.
EU.3	Plan transport possibility.			Transport possibilities should be considered when designing a product. These can be realized for example by eyes or grips so the products can be moved easier, and by reduced size and weight. Transportable products can be used at different places with little time and work effort.
EU.4	Make use of additional interfaces.			It can be useful to equip the product with more interfaces than initially required, to ease upgrading, up-scaling and extending. When new or changed requirements occur the initial product does not have to be redesigned and adapted, as the changes and requirements are already covered by the existing product.
EU.5	Make use of simple and clear symbols to explain handling.			Making use of simple and clear symbols to explain the product handling enables the use of the product in various countries or cultures and environments without adapting the product to the specific market. The labeling with simple symbols enhances the number of potential users and reduces the probability of later redesign.
EU.6	Make use of adjustable system and module output parameters.			If the system or module output is adjustable instead of static the flexibility of the product increases, because different demands can be simply realized without adapting the product. The adaptation could be carried out if necessary by the users themselves.

Table A2 - 7 Design guidelines Over-Engineering (OE)

Over-Engineering (OE)				
#	*guideline*	*not flexible*	*flexible*	*explanation*
OE.1	Plan options for add-ons and add-on systems.			The functions of a product can be simply adapted to changed demands by the use of add-ons. Simple standardized interfaces must be defined between product and add-on already in the planning phase. The product can be simply adapted by connecting specific add-ons depending on the situation.
OE.2	Create buffer zones.			Creating buffer zones enhances the flexibility of a product, as these allow to accommodate larger parts and modules without redesigning the whole product.
OE.3	Plan redundancies.			To enhance the flexibility of a product, redundancy of specific parts, modules and features should be considered during product planning and designing. If for example requirements change with regard to the geometry, these are maybe already covered by the redundantly designed parts, modules or features. The product can be adapted in small steps simply to the new conditions. This way a costly redesign of the component or product is avoided.
OE.4	Choose technologies that are far from obsolete.			A technology should be used, which does not become outdated too fast and has matured - a technology that is far from obsolete. This reduces the likelihood of future changes. The possibility of changes due to the application of not yet mature technology is reduced, so that all together less changes must be carried out.
OE.5	Over-size with regard to stress.			If a product is over-sized with regard to the expected stress, the product can be also used if the external conditions result in higher stress. The over-sizing can be achieved for example, by enhancing wall size or by using more efficient materials.
OE.6	Over-size with regard to power and energy.			Products can be over-sized with regard to power and energy. This increases the application range of the product and thereby the likelihood of future changes, even if the product requirements further intensify.
OE.7	Over-size with regard to geometry and available space.			A product over-sized with regard to the geometry and available space can also be used when the future requirements are different. The guideline aims at an "exaggeration" of the original requirements - expecting that these develop further in this direction. I.e. if the requirement is "large, minimum 500 mm", the product or part should be dimensioned even larger, for example "minimum 700 mm"; when the requirement is "small, maximum 12 mm" the product or part should be designed even smaller, for example "maximum 8 mm", than originally demanded.

A3 Questionnaires used in Laboratory Study

Table A3 - 1 Questionnaire T0

Questionnaire: T0 Participant:

1. How do you rate your current stress?	not stressed	☐	☐	☐	☐	☐	☐	extremely stressed
2. How do you rate your current motivation?	not motivated	☐	☐	☐	☐	☐	☐	extremely motivated
3. How content are you with your work and the progress so far?	not content	☐	☐	☐	☐	☐	☐	extremely content
4. I understand the design task.	does not apply at all	☐	☐	☐	☐	☐	☐	fully applies
5. I think the design task is challenging.	does not apply at all	☐	☐	☐	☐	☐	☐	fully applies
6. I think the design task is interesting.	does not apply at all	☐	☐	☐	☐	☐	☐	fully applies

7. Have you worked with these kind of gardening tools before? yes ☐ ☐ no

8. How much time do you assumingly need to finish the design task? expected overall time (concept + design) ....

9. Comments?

Please, mark clearly on the sheet with guidelines every time you intentionally use a guideline.

Table A3 - 2 Questionnaires T10 –T170 (questionnaire T70 used as example)

Questionnaire: T70 Participant:

1. How do you rate your current stress? **not stressed** ☐ ☐ ☐ ☐ ☐ ☐ **extremely stressed**

2. How do you rate your current motivation? **not motivated** ☐ ☐ ☐ ☐ ☐ ☐ **extremely motivated**

3. How content are you with your work and the progress so far? **not content** ☐ ☐ ☐ ☐ ☐ ☐ **extremely content**

4. How much time do you assumingly need to finish the design task? **expected overall time (concept + design)** ....

5. How much of the overall results did you achieve so far? Please estimate the percentage of your current result with respect to the overall result. **Assumed percentage of overall result (concept + design)** ....

6. How well are you prepared to handle the changes? **not at all** ☐ ☐ ☐ ☐ ☐ ☐ **very well prepared**

7. What task have you been working on **within the last 10 minutes**?

	partly worked on	intensively worked on
Searching requirements	☐	☐
Organizing and checking requirements	☐	☐
Identifying problems	☐	☐
Formulating functions and creating function structure	☐	☐
Searching working principles and working structures	☐	☐
Evaluating variants and solutions	☐	☐
Checking for flaws	☐	☐
Defining concept	☐	☐
Searching for dimension and layout determining requirements and defining main geometrical constraints	☐	☐
Roughly designing main functions	☐	☐
Roughly designing sub functions	☐	☐
Designing details	☐	☐
Evaluating design	☐	☐
Optimizing design, checking and completing	☐	☐
Implementing changes	☐	☐

not worked on at all = please do not check any of the boxes

8. Comments?

Please, mark clearly on the sheet with guidelines every time you intentionally use a guideline.

Table A3 - 3 Questionnaire T180-1

Questionnaire: T180-1 Participant:

1. How do you rate your current stress? — not stressed ☐ ☐ ☐ ☐ ☐ ☐ extremely stressed

2. How do you rate your current motivation? — not motivated ☐ ☐ ☐ ☐ ☐ ☐ extremely motivated

3. How content are you with your work and the progress so far? — not content ☐ ☐ ☐ ☐ ☐ ☐ extremely content

4. How much time do you assumingly need to finish the design task? — expected overall time (concept + design) ……………

5. How much of the overall results did you achieve so far? Please estimate the percentage of your current result with respect to the overall result. — Assumed percentage of overall result (concept + design) ………………

6. How well are you prepared to handle the changes? — not at all ☐ ☐ ☐ ☐ ☐ ☐ very well prepared

7. What task have you been working on **within the last 10 minutes**?

	partly worked on	intensively worked on
Searching requirements	☐	☐
Organizing and checking requirements	☐	☐
Identifying problems	☐	☐
Formulating functions and creating function structure	☐	☐
Searching working principles and working structures	☐	☐
Evaluating variants and solutions	☐	☐
Checking for flaws	☐	☐
Defining concept	☐	☐
Searching for dimension and layout determining requirements and defining main geometrical constraints	☐	☐
Roughly designing main functions	☐	☐
Roughly designing sub functions	☐	☐
Designing details	☐	☐
Evaluating design	☐	☐
Optimizing design, checking and completing	☐	☐
Implementing changes	☐	☐

not worked on at all = please do not check any of the boxes

8. Comments?

Please, mark clearly on the sheet with guidelines every time you intentionally use a guideline.

Table A3 - 4 Questionnaire T180-2

Questionnaire: T180-2 Participant:

9. What were the two most positive experiences during the study?

10. What were the two most negative experiences during the study?

11. Do you consider working with the guidelines as additional stress? **no additional stress** ☐ ☐ ☐ ☐ ☐ ☐ **high additional stress**

12. Did you have advantages due to applying the guidelines? What kind of?

13. Did you have disadvantages due to applying the guidelines? What kind of?

14. The guidelines help to design flexible products. **do not agree at all** ☐ ☐ ☐ ☐ ☐ ☐ **completely agree**

15. Flexible products are useful to handle changes. **do not agree at all** ☐ ☐ ☐ ☐ ☐ ☐ **completely agree**

Please turn page.

Table A3 - 5 Questionnaire T180-3

Questionnaire: T 180-3 Participant:

Modularization and Decoupling			
	Do you understand the guideline?	Did you use the guideline?	How do you rate the support provided by the guideline?
MD.1	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
MD.2	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
MD.3	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
MD.4	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
MD.5	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
MD.6	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
MD.7	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
MD.8	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
MD.9	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive

Inherent Flexibility			
	Do you understand the guideline?	Did you use the guideline?	How do you rate the support provided by the guideline?
IF.1	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
IF.2	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
IF.3	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
IF.4	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
IF.5	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
IF.6	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive

Table A3 - 6 Questionnaire T180-4

Questionnaire: T 180-4 Participant:

Easy (Dis-) Assembly (DA)

	Do you understand the guideline?	Did you use the guideline?	How do you rate the support provided by the guideline?
EA.1	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
EA.2	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive

Standardizing

	Do you understand the guideline?	Did you use the guideline?	How do you rate the support provided by the guideline?
ST.1	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
ST.2	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
ST.3	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
ST.4	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive

Extended Use

	Do you understand the guideline?	Did you use the guideline?	How do you rate the support provided by the guideline?
EU.1	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
EU.2	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
EU.3	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
EU.4	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
EU.5	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive
EU.6	do not understand ☐☐☐☐☐☐ fully understand	yes ☐☐ no	rather hindering ☐☐☐☐☐☐ rather supportive

Table A3 - 7 Questionnaire T180-5

Questionnaire: T 180-5 Participant:

Over-Engineering			
	Do you understand the guideline?	Did you use the guideline?	How do you rate the support provided by the guideline?
OE.1	do not understand □□□□□□ fully understand	yes □□ no	rather hindering □□□□□□ rather supportive
OE.2	do not understand □□□□□□ fully understand	yes □□ no	rather hindering □□□□□□ rather supportive
OE.3	do not understand □□□□□□ fully understand	yes □□ no	rather hindering □□□□□□ rather supportive
OE.4	do not understand □□□□□□ fully understand	yes □□ no	rather hindering □□□□□□ rather supportive
OE.5	do not understand □□□□□□ fully understand	yes □□ no	rather hindering □□□□□□ rather supportive
OE.6	do not understand □□□□□□ fully understand	yes □□ no	rather hindering □□□□□□ rather supportive
OE.7	do not understand □□□□□□ fully understand	yes □□ no	rather hindering □□□□□□ rather supportive

All guidelines as a set			
	Do you understand the guideline?	Did you use the guideline?	How do you rate the support provided by the guideline?
All	do not understand □□□□□□ fully understand	yes □□ no	rather hindering □□□□□□ rather supportive

A4 Design Task

Table A4 - 1 Design Task including initial requirements list

Design Task

Task:

Generate a concept and design for an apparatus to shred garden waste

The number of the garden owners becomes bigger and bigger. In the course of one garden year large amounts of green, branches and brushwood can accrue. This results in following problem: Where to put the garden waste? An apparatus to shred garden waste offers the optimum solution. The waste volume is reduced and the shredded waste is suited very well for the composting or the stubble mulching. The wood is supplied by hand, is chopped up by a suitable mechanism and ejected.

Requirements and Constraints:

Drawing scale 1:3

Waste supply vertically form the top

Waste ejection vertically downwards

Electrical drive train, engine 1 kW, dimensions see engine data sheet, integrated in product housing

Save state

Easy transport

Compact design

Garden waste: green, branches, brushwood to diameter 45 mm

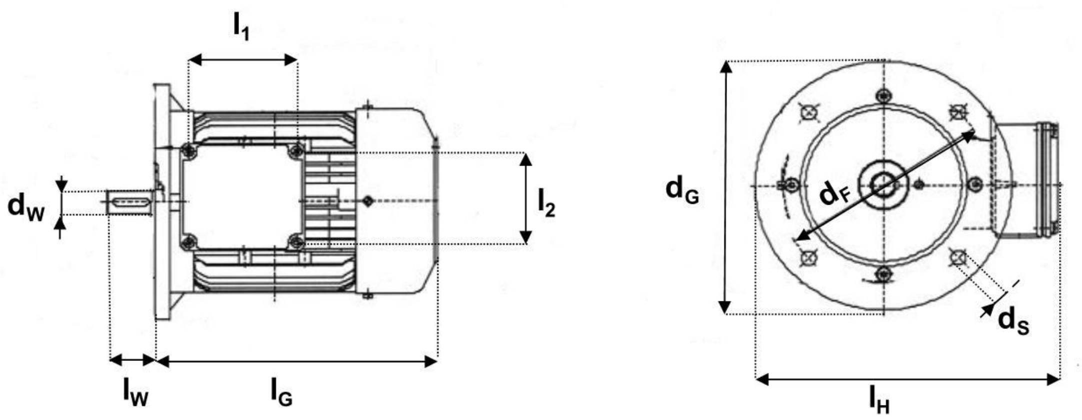
Size of the shreds max. 30 mm

maximum height top edge supply: 1650 mm

minimum height ejection: 450 mm

Table A4 - 2 Initial electrical engine data sheet

Engine data sheet



Electrical engine 1 kW

Cam end with internal thread DIN 332 D, thread= M6x20
Parallel key according to DIN 6885, detailed dimensions not relevant
Fit for cam end: ISA k6
Flange without thread, four drillings with d_S = 12 mm

l_1 = 80 mm
l_2 = 70 mm
l_G = 200 mm
l_W = 40 mm
d_W = 24 mm
d_G = 180 mm
l_H = 220 mm
d_F = 140 mm
d_S = 12 mm

Table A4 - 3 Changes and additions 30 and change questionnaire CQ1

Additions/Changes 30

All not changed requirements continue without limitation

This change led to:

	No effect on present work	Partly redesign	Complete redesign of present work	Starting time of implementing this change:	Finishing time of implementing this change:
Transport through door (BxH): 900mm x 1800mm	☐	☐	☐	---------	---------

This change led to:

	No effect on present work	Partly redesign	Complete redesign of present work	Starting time of implementing this change:	Finishing time of implementing this change:
Minimal diameter supply: 150mm	☐	☐	☐	---------	---------

This change led to:

	No effect on present work	Partly redesign	Complete redesign of present work	Starting time of implementing this change:	Finishing time of implementing this change:
Divisible housing for maintenance and cleaning	☐	☐	☐	---------	---------

Table A4 - 4 Changes and additions 90 and change questionnaire CQ2

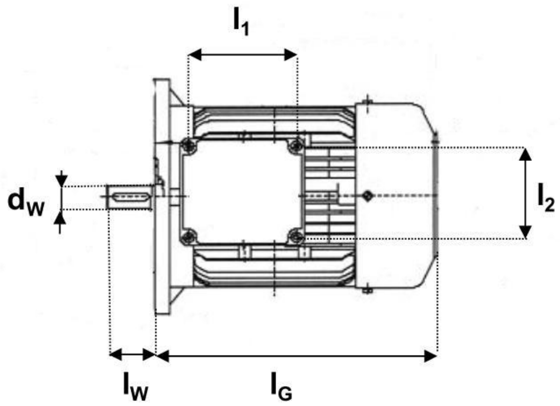
Additions/Changes 90

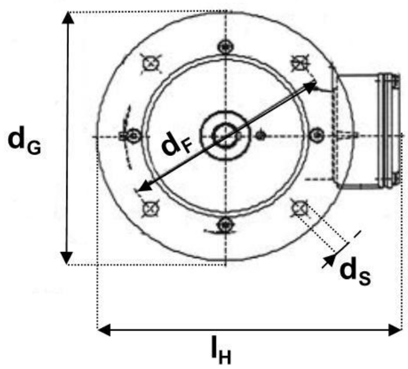
All requirements that are not changed continue to be valid

Addition/Change	This change led to: No effect on present work	Partly redesign	Complete redesign of present work	Starting time of implementing this change:	Finishing time of implementing this change:
Electrical engine (2kW) see engine data sheet 2, integrated in product housing	☐	☐	☐	---------	---------
Easy transport with rolls	☐	☐	☐	---------	---------
Shreds size adjustable without tool between 10 and 30 mm	☐	☐	☐	---------	---------
Possibility for rolling up the electrical cable	☐	☐	☐	---------	---------
maximal storage dimensions (LxWxH): 600mm x 600mm x 1500mm	☐	☐	☐	---------	---------

Table A4 - 5 Electrical engine data sheet 90

Engine data sheet 2 (90)





__Electrical engine 2 kW__
Cam end with internal thread DIN 332 D, thread= M6x20
Parallel key according to DIN 6885, detailed dimensions not relevant
Fit for cam end: ISA k6
Flange without thread, four drillings with d_S = 12 mm

l_1 = 80 mm
l_2 = 70 mm
__**l_G = 280 mm**__
l_W = 40 mm
d_W = 24 mm
__**d_G = 220 mm**__
__**l_H = 260 mm**__
d_F = 140 mm
d_S = 12 mm

Table A4 - 6 Changes and additions 120 and change questionnaire CQ3

Additions/Changes 120

All not changed requirements continue without limitation

This change led to:

Maximum height top edge supply: 1350mm

No effect on present work	Partly redesign	Complete redesign of present work	Starting time of implementing this change:	Finishing time of implementing this change:
☐	☐	☐	---------	---------

This change led to:

Minimal height ejection: 600mm

No effect on present work	Partly redesign	Complete redesign of present work	Starting time of implementing this change:	Finishing time of implementing this change:
☐	☐	☐	---------	---------

This change led to:

Minimal diameter supply: 180mm

No effect on present work	Partly redesign	Complete redesign of present work	Starting time of implementing this change:	Finishing time of implementing this change:
☐	☐	☐	---------	---------

This change led to:

Device to collect shreds, which can be (dis-) mounted without tools

No effect on present work	Partly redesign	Complete redesign of present work	Starting time of implementing this change:	Finishing time of implementing this change:
☐	☐	☐	---------	---------

This change led to:

Save stand on a sloping ground (angle of slope: 10 degrees)

No effect on present work	Partly redesign	Complete redesign of present work	Starting time of implementing this change:	Finishing time of implementing this change:
☐	☐	☐	---------	---------

A5 Profiles of Participants

Table A5 - 1 Participants' Background

participant number		G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	W1	W2	W3	W4	W5	W6	W7	W8	coding points and weight factors for skill value
study																				
cours of study*		TE	ME	ME	ME	TE	TE	TE	IE	IE	TE	IE	IE	ME	ME	ME	IE	TE	TE	TE/ME = 10, otherwise 0
term of study		6	7	11	7	11	5	5	6	9	12	9	9	7	13	10	8	12	9	per term 1
focus of study**		AST		ED	ME	VT	AST	AST	TE	MD	AST	MD	MD	MT	ED	PT	MD	VT	AST	ED = 4, otherwise 0
aspired degree																				
Diplom (~Master)	yes/no	●	●	●	●	●			●	●	●	●	●	●	●	●	●	●	●	yes = 3
Bachelor	yes/no						●	●												yes = 1
passed Bach.Deg. (Vordiplom)	yes/no	●		●	●	●				●	●	●	●	●	●	●	●	●		yes = 3
attended related courses																				
Engineering Design I/II	yes/no	●	●	●	●	●	●	●			●			●	●	●		●	●	yes = 3
Engineering Design III	yes/no	●	●	●	●	●	●	●			●			●	●	●		●	●	yes = 4
Engineering Design IV	yes/no	●	●	●	●		●	●			●			●	●	●		●	●	yes = 5
Systematic Product Development	yes/no		●	●	●	●	●	●							●					yes = 2
Machine Design	yes/no		●	●	●										●			●		yes = 1
Quality Management	yes/no								●		●		●							yes = 1
Machine Elements	yes/no								●	●		●	●				●			yes = 7
Manufacturing Technology	yes/no			●	●					●					●	●				yes = 1
internships																				
	0 [0] 1-8 [1] 9-16 [2] >16 weeks [3]	2	2	1	1	2	1	1	2	2	3	3	2	3	2	3	2	2	3	0/1/2/3
student work																				
attended student design project	yes/no			●								●		●	●	●				yes = 2
passed student research project	yes/no					●					●			●		●				yes = 2
student research assistent	since [months]					6					24			6				21	8	not considered
student research teacher	since [months]	2	3	21	2	19	3	3	3	9	0	27	8	2	34	35	17	21		per month 0.2
technical background																				
		no	no	no	no	no	no	no	no	no	no		no	no	no	no	no	no	industrial mechanic	for ind. mech. 5

* TE = Transportation Engineering
ME = Mechanical Engineering
IE = Industrial Engineering

** AST = aero and space technology
ED = engieering design
VT = vehicle technology
MD = machine design
MT = materials technology
PT = production technology