

GUIDELINES FOR THE DEVELOPMENT OF FLEXIBLE PRODUCTS

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1. Introduction

The requirements for technical products are getting more complex and more diverse. Single products have to fulfil a great variety of demands and wishes, to be competitive. Even more complex the requirements change during product life cycle fast and several times. Companies have to define adequate strategies to handle this challenge.

Flexibility is suggested as one useful instrument for companies, to remain competitive in fast changing markets [e.g. Thomke 1997]. Beside flexible production technologies and processes this flexibility also includes the development of flexible products. These products can easily be adapted to the fast changing and versatile requirements of the customers [Singh 2004].

1.1 Task

There are many approaches to support the development of flexible products, [e.g. Palani Rajan 2003, Stone 1997, Hashemian 2005]. Most of them are based on few textual guidelines, which are used as supportive tools for the systematic product development. Some of these approaches are limited to simple description of the properties of flexible products. There is no comprehensive collection of all approaches and the underlying guidelines to be found in literature.

1.2 Aim

In the past many different product development guidelines for the development of technical products have been published to handle specific tasks [Pahl 2007]. One example is the set of guidelines, which are collected under the “Design for Production” label. These different guidelines and foci are nowadays usually described by the term “Design for X” (DfX) [Pahl 2007].

Within the DfX area there is a great number of guidelines, which support the systematic development of flexible (DfF) [Palani Rajan 2003], modular (DfM) [Stone 1997] and adaptable (DfA) [Hashemian 2005] products. These partly contrary product development guidelines were collected and clustered by their principle of flexibility. Moreover the textual guidelines are visualised to gain a better and faster understanding and improve the memorability.

1.3 Approach

Basis for this comprehensive collection of flexible product development guidelines is a broad literature research for the topic “development of flexible products”. Besides terms like “flexible” and “adaptable”, “expandable”, “versatile”, “modular” the research included for example “platform design” to identify all guidelines for this approach. The results of this research were used in a practical project [Bischof 2006] and partly validated. The practical project led to more ideas for new guidelines for the development of flexible products. All collected and generated guidelines were tested in a

laboratory study with engineering design students. This study approved that a sole textual presentation of product development guidelines is not adequate to support the development of flexible products [Bischof 2007].

From instructional design it is known that pictures and illustrations support the learning process better than only textual information [Weidenmann 1991]. Till now the product development guidelines for DfF, DfM and DfA were published textual only [e.g. Palani Rajan 2003]. We hope that the idea to visualise them will lead to positive feedback, a better understanding and a improved knowledge transfer. So the new formed set of guidelines was transferred to symbolic graphics, as they are used in engineering design education for decades. These graphic based product development guidelines cannot only be used for teaching, but also in reference books for a fast and simple knowledge transfer (e.g. 'Design for Production' in [Pahl 2007]). The new graphical guidelines for the development of flexible products were presented with a positive feedback already on the German 18th DfX-Symposium [Bischof 2007b] and are now translated for a broader accessibility.

2. Flexible product

2.1 Flexibility and flexible products

Many different terms as e.g. "flexibility", "changeability", "versatility" and "adaptability" are used in literature to describe similar, but not identical aspects of the product development process (PDP) and properties of technical products. In following the terms "flexibility" and "flexible" are used as generic terms, which include the above mentioned terms and their underlying ideas.

Flexibility can be defined to be the incremental time and cost of modifying a design as a response to changes exogenous (e.g. shifting customer needs) or endogenous (e.g. the discovery of a better solution approach) to the design process [Thomke 1997].

Following this definition flexible products are here defined as products, which can be adapted to changed need and requirements with little amount of time and costs within the development phase as well as during the rest of the product life cycle. Thus a product contains highest flexibility, if it does not have to be adapted at all when changes occur, because the new requirements are covered by the original product.

Figure 1 and 2 show examples of flexible products, which can be adapted to new conditions easily with little amount of time and costs. The examples demonstrate the wide range of products to be considered flexible.

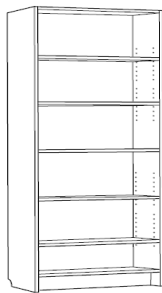


Figure 1. Flexible shelf system

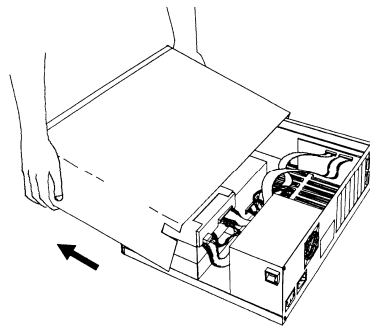


Figure 2. Housing of desktop PC

The shelf system (cf. figure 1) is defined as flexible, because it can easily be adapted to changed requirements. It built up and dismantled several times in its life cycle. New shelves can be added. It can be extended horizontally and vertically. It can be transferred into a glass cabinet. The inherent flexibility is accomplished by applying different design criteria, which can be found in the set of guidelines presented in section 4 (cf. table 1). The implementation of following guidelines can be

identified in a standard scaffold: 1, 3, 9, 10, 12 and 24. Depending on how it is built up, additionally the implementation of guidelines 4, 6, 18, 20 and 21 can be detected.

Figure 2 shows the housing of a desktop PC. It can easily be opened, so that the PC can be adapted and additional components (modules) can be added later, when requirements of the user have changed. The standardised slots, plug-in positions and connectors allow easy (dis-)assembling as well during production as for the user. The implantation of following guidelines can be detected on the housing of the PC: 1, 3, 4, 9, 10, 12, 13, 14 and 18 (depending on configuration: 19, 22, 24).

2.2 Product development guidelines in context of „flexibility”

Often the related research is focused on one single aspect of flexibility, namely the ability of products to suit customer requirements, if these vary substantially or change fast. Many ideas of the related research thus concentrate on product specification and on embodiment and structure of products when already launched (either to allow changes during the product's life or to allow individualisation of the product). Flexibility of products while being developed to cope with yet unknown requirements is mainly neglected. In the following the main foci of various approaches are summarised.

Remaining flexible

The idea of remaining flexible (in a generic sense) throughout a PDP in a rapidly changing environment and thus remaining competitive was already proposed by Thomke and is still the focus of current research [Thomke 1997]. His work is on a more general level: He and others do not propose guidelines or other practical tools for product developers. He instead focuses on the importance of agile acting and reacting during the PDP [Thomke 1997] for designers and all other involved people within the company.

Design for Flexibility

Palani Rajan et al. [2003] define product flexibility as the degree of responsiveness (or adaptability) to any future change (e.g. new requirements) in a product design. To Design for Flexibility (DfF) they propose a method of measuring a product's flexibility analogous to Failure Mode and Effect Analysis. This so called Change Mode and Effects Analysis (CMEA) is a systematic aid in understanding how some future change might affect a product. They also propose flexibility guidelines for designers to change the design based on the results from the CMEA. These guidelines could be added to the new comprehensive collection.

Design for Modularisation

Modularity is a major issue in research on flexible products [e.g. Stone 1997]. Modular Function Deployment (MFD) as presented by Erixon [1998] is one approach used to modularise a product in order to allow it to be changed more easily when changes occur during PDP or to be adapted to new requirements in later phases of product life. Changes can be made on module level and do not necessarily affect the whole system. Design for Modularisation does not give precise instructions how to design the modules of a product, but it is used to define module structures and the interfaces. Sosa et al. [2000] propose modular design not only on assembly level, but as well on system level. A useful modularisation of products is often mentioned with high importance in the DfF approach. Thus guidelines from DfM or MFD have to be taken into account, when developing flexible products.

Flexible Product Platforms

The concepts of product platform and product architecture are strongly related to the modularisation concept. Hölltä-Otto defines modular product platforms as sets of common modules that are shared among a product family. She does not only propose a tool to identify alternative common modules but also presents “a multi-criteria platform scorecard for improved evaluation of “goodness” of modular platforms” [Hölltä-Otto 2005].

Design for Variety

Design for Variety (DfV) is another approach to design products to meet the diverse customer requirements [Martin 2002]. The idea is to build a series of similar products based on the same product architecture. Martin and Ishii [2002] quote Ulrich [2003], who defines architecture as a scheme by which the function of a product is allocated to physical components. Using their DfV approach, it is possible to create a great variety of products with minimal design effort, so that many different customers can be served. Contrary to size ranges the DfV allows to create not only products of different geometry, but the adaptation and exchange of different functionalities. The product architecture is of high importance for the DfV, because it is basis not only for one product, but for a series of different products, which is similar to the product family as mentioned by Hölltä-Otto [2005]. Van Wie [2002] describes a systematic method for creating a useful product architecture for the concept of DfV. He distinguishes between two types of drivers causing redesign: internal drivers (e.g. a change from one concept to another) and external drivers (e.g. shifting customer needs). To avoid redesign, the DfV method prescribes steps and heuristics for developing the product architecture less sensitive to future changes.

Design for Changeability

There are different interpretations of the concept of Design for Changeability (DfC). While Schuh et al. [2005] focus on the flexibility of the production process and its machinery (e.g. Flexible Production System - FPS), Fricke et al. present different “principles to enable changes in systems throughout their entire life cycle” [2005]. As products are part of systems and can have a comparable high complexity, the distinction between products and systems is neglected here and the presented principles are transferred from systems engineering to product development. Fricke et al. develop the idea of incorporating changeability into system architecture. Flexibility, agility, robustness, and adaptability as four key aspects of changeability are defined and described. To achieve changeability in a system, they propose several design principles.

Design for Adaptability

Design for Adaptability is presented by Hashemian with a focus on the extended utility of products [2005]. He describes a way of designing products that can be adapted to different requirements with a specific and a general Adaptable Design (AD) approach. Specific AD is proposed to be performed first to take advantage of available forecast information, and then general AD has to be performed in order to increase adaptability to unforeseen changes. Methods and guidelines, which help to design adaptable products, are proposed as well as a measure for the assessment of adaptability.

Adaptronics

Besides the approaches of creating a flexible design with specific methods and guidelines, there is the idea of using special parts to create products that autonomously adapt to changed situations. This concept, called adaptronics, aims at developing construction structures that continuously fulfil their tasks by reactively adapting themselves to changes in loading and required functionality by integrating actuators and sensors in the construction structure as multifunctional materials [Pahl 2007]. Thus they are combining mechanical structures with control and information technology.

Design for Assembly

A lot of research has been carried out in order to improve the assembly process [e.g. Andreasen 1988, Rampersad 1996]. The approach is named Design for Assembly (DfA) or more comprehensive Design for Manufacture and Assembly (DFMA) [e.g. Kalpakjian 1995]. Design criteria and design guidelines are proposed in order to design products, which are easy to assemble (disassembly is not always considered). An (dis-)assembly optimized product can help to reduced time and cost, when the product has to be reconfigured or dismantled in order to change some parts and/or modules. Referring to the definition (cf. section 2.1) the product is more flexible. Thus, the DfA guidelines are partly applicable for designing more flexible products.

Combining different approaches

All approaches that are mentioned above deal with the idea that products have to be designed in a flexible way in order to deal with the great variety in requirements (individualisation) or to handle changing requirements during product life. Some offer precise instructions for the development of new products. Other approaches are more abstract and less practical when solving a concrete development problem. None of the analysed methods deals with designing a product, i.e. gradually fixing its properties, while at the same time keeping the options open to remain flexible during the PDP. In order to archive product flexibility already during the early phases of the PDP the different ideas are combined to a new approach. This approach is based on set of product development guidelines. These guidelines were already published with the graphical illustrations at the 18th DfX Symposium [Bischof 2007b] and are now being translated to be accessible to a wider audience.

3. Graphic instructions

In literature many product development guidelines are explained by additional graphics showing either the principle or an example of its application. Examples are the “Design for Production” guidelines as shown in [Pahl 2007]. The approaches and guidelines mentioned above are only textual and thus more difficult to understand [Weidenmann 1991]. In dependence on the well known graphical product development guidelines here the collected textual guidelines are explained graphically (cf. section 4). The basics of instructional design are taken into account in order to archive a better understanding. The instructional design deals among other topics with the analysis and development of graphical illustrations for teaching material. In following a short overview of the function and design of illustrations is given.

3.1 Effect and function of illustrations

Illustrations can archive different functions [Levin 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 organise the connected structures and thus make the text more understandable.

Levie and Lentz 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 [1982]. Especially for understanding complex coherences, illustrations support the understanding and learning process more effectively than textual explanations only [Mayer 1990].

If learning time is limited the reduced graphic illustrations, as to be found in the standard literature of engineering design [e.g. Pahl 2007], are very supportive. Only if there is a huge amount of time for watching, more detailed and realistic illustrations have higher effectiveness [Dwyer 1972].

Colours 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 colour in one illustration can have negative effects on understanding and remembering due to increasing complexity.

3.2 Optimisation Illustrations

Different requirements can be derived from the study of Mayer [1990], which have to be fulfilled in order to effectively support the understanding of scientific texts with help of illustrations:

- 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.

3.3 Applying findings from instructional design for graphical translation of guidelines

When visualising the flexibility guidelines the textual formulations were checked and adapted for clear and better understanding. If possible, the illustrations were designed in a self descriptive way. As watching time is mostly limited, the illustrations are designed as simple as possible. All illustrations are black and white only. No additional colour increases complexity. Thus, they also better fit into the context of guidelines visualised in engineering design literature so far. Basic technical knowledge on the beholders' side was assumed.

4. Guidelines for the Development of Flexible Products

“Guidelines are information intended to advise people on how something should be done or what something should be” [Cambridge Advanced Learner’s Dictionary 2006]. Aim of applying guidelines in product development is to make the results of the activities of the designers more predictable and to presumptively improve the results. The flexibility guidelines, which are presented here, are already tested in a design project. First benefits of this approach could already be presented [Bischof 2006]. Using these guidelines helped the design engineers, when uncertainties occurred during the design process. It was possible to adapt new functions later without changing the whole product concept.

4.1 Principles of flexibility

Related to the given definition of flexible products, the principles of flexibility can be categorized in three different ways. All of them make the product more flexible, thus time and/or cost for potential changes are reduced or eliminated:

Reduce the effort of changing procedure - CP

This principle of flexibility deals the changing procedure itself. As the probability of future requirement changes is high – especially in innovative new product development projects – the aim is to simplify the changing procedure of the product. The product has to be designed in a way that no matter why and when the changes occur they can be executed easily.

“Plan unambiguous (dis-)connection techniques/plan disconnecting” is one example for a guideline using the first principle of flexibility. Unambiguous connections between the parts of the products and well planned disconnecting techniques help to simplify the changing procedure. The execution of the simplified change procedure requires less time and costs compared to a changing procedure on a product, where the connection and disconnection techniques are planned less unambiguous.

Reduce the effect of changes - EC

The second principle of flexibility aims at reducing the negative effects on different parts of the product, when a changing procedure is necessary only for one singular part. These negative effects are mainly additional changing procedures that have to be done due to the initial changing. This can cause an avalanche effect so that many different parts of the product have to be adapted. In the worst case these adaptations lead to a redesign that is as time and money consuming as a complete new product development. Applying this principle of flexibility helps to reduce the negative effects of the initial (requirement) changes.

Many product development guidelines are based on this principle. “Increase number or size of virtual or actual buffer zones” suggested in Design for Flexibility by Palani Rajan [2003]. The idea is to reduce the coupling of components. The stronger the coupling between components, the more likely a change in one will require a change in the other. Two components are considered coupled if a change made to one of the components requires the other component to be changed as well [Palani Rajan 2003]. Creating e.g. a large amount of void space within a product and/or a single part of it leaves room for later adaptations. Being able to implement the adaptations in this predefined area uncouples them from the other parts and areas of the product. Thus the negative avalanche effect is interrupted immediately. The amount of time and costs are reduced. Corresponding with the given definition the product is more flexible.

Reduce the occurrence of changing the product - OC

Reducing the probability of occurrence of changing the product is the third principle of flexibility that can be used. It can be divided into two sub principles itself. First develop the product in a way that it is well prepared for future changes and second, already implement possible new requirements when developing the product the first time.

Mainly this point is about forecasting possible future changes and keeping them in mind when developing the product. If the product is already adapted to these forecasted changes it is less likely that changing on the product occurs during the product life time.

There are many different methods and methodologies that can be used in the PDP to forecast future market needs and customer requirements. Additionally guidelines are defined, which support the systematic development process. These guidelines make use of the described principle of flexibility. Among them there is e.g. “select technology, which is far from obsolete” [Palani Rajan 2003]. Thus changes caused by switches to newer technology during product life cycle are avoided, respectively reduced. Using only the newest technology is not suggested and not implied in the set of guidelines, as it tends to cause changes itself, because it is often poorly conceived.

Reducing the probability of future changes leads to fewer product changes and less adaption to new requirements. So summed up over product life cycle, time and costs for changing the product are reduced. Based on the given definition this makes the product more flexible.

4.2 Product development guidelines for flexible products

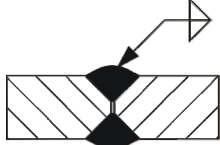
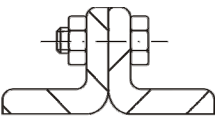
Table 1 lists the collected and visualised development guidelines. They are clustered in three categories, following the three principles of flexibility elucidated above. Following three examples are presented to explain the guidelines briefly.

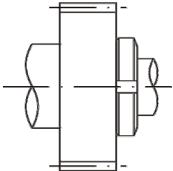
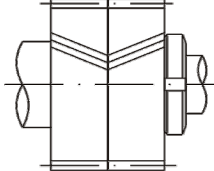
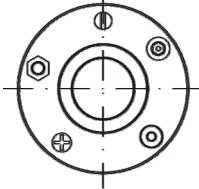
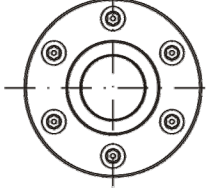
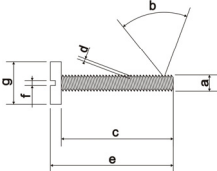
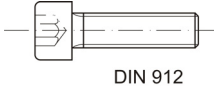
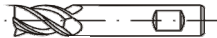
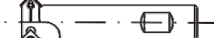
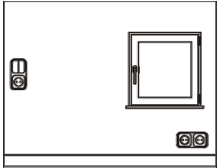
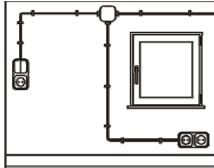
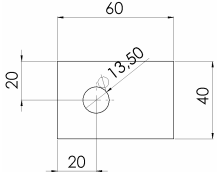
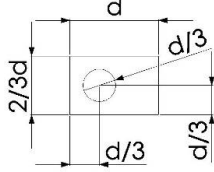
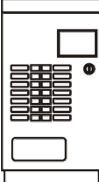
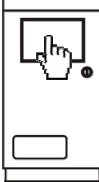
Guideline #1 “Plan definite (dis-)connecting devices and consider disconnecting from the beginning” mainly aims at the first principle of flexibility – “reduce the effort of changing procedure - CP”. By planning definite connecting devices and consider the disconnection when planning the product it is assured, that the product can easily be disassembled when changes occur and the product has to be adapted. By the simplified changing procedure the costs and time for adapting the product are reduced and thus it is more flexible in terms of the given definition.



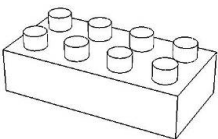
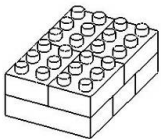
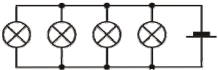
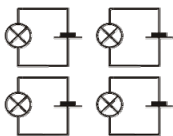
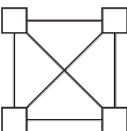
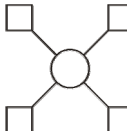
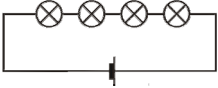
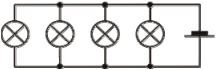
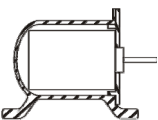
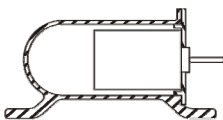
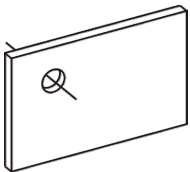
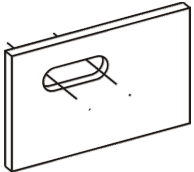
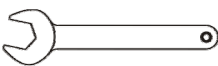


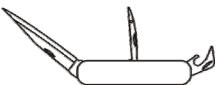
Guideline #10 “Increase the number of modules” mainly aims at the second principle of flexibility – “reduce the effect of changes - EC”. By designing the product more modular and thus creating many intersections the single parts of the product become more independent and less effected by changes in other parts and modules of the product. The chain reaction of changes is interrupted. Less adaptation and changing occur for the whole product.

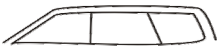
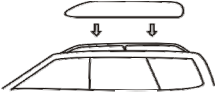
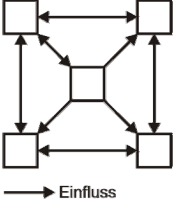
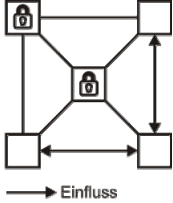


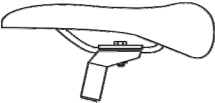
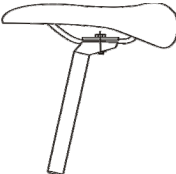

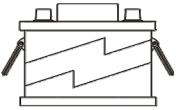
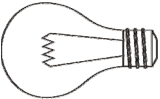
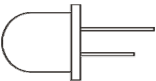
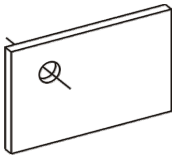
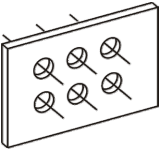
The third principle of flexibility – “reduce the occurrence of changing the product - OC” - is for example used by guideline #23 “choose technologies that are far from obsolete”. By applying this guideline when developing a new product the probability of changes and adaptation of the product is reduced. Using “technology that is far from obsolete” keeps the product up-to-date for a long time. Using “old technologies” would raise the probability for upgrades in near future, while “latest technology” tends to be poorly conceived and thus often has to be changed and adapted. The probability of changes is smallest for “technology far form obsolete” and thus these kinds of products are most flexible according to the given definition.

Table 1. Guidelines for the development of flexible products

#	GUIDELINE	NON FLEXIBLE	FLEXIBLE	PRINCIPLE*
1	Plan definite (dis-) connecting devices and consider disconnecting from the beginning.			CP, (EC)

2	Use self adjusting and self curatively designs if possible.			CP, (EC)
3	Define a limited number of interfaces and interface variants.			CP, (EC)
4	Use standard machine elements and standard parts. Set own standards.		 DIN 912	CP, (EC)
5	Place fast wearing parts and replacement parts at the outside of the product.			CP, (EC)
6	Put individualised custom parts at the outside of the product.			CP, (EC)
7	Use parametric design.			CP, (EC)
8	Implement software instead of hardware solutions.			CP, EC

9	Subdivide the product in modules. Use differential instead of integral design.			EC, CP
10	Increase the number of modules.			EC, CP
11	Plan autonomous modules.			EC, CP, OC
12	Minimise the internal connections. Use bus systems.			EC, CP, OC
13	Reduce internal dependencies.			EC, OC, CP
14	Create buffer zones.			OC, EC, (CP)
15	Use flexible and change-tolerant design features and machine elements.			OC, EC, CP
16	Create universal designs.			OC, EC, CP
17	Plan additional functions and configurations from the beginning.			OC, (EC, CP)

18	Plan options for add-ons and add-on systems.			OC, (EC, CP)
19	Block and/or freeze parts, assembly groups and modules if possible.			OC, (EC, CP)
20	Oversize related to stress.			OC
21	Oversize related to geometry and available space.			OC
22	Oversize related to power and energy.			OC
23	Choose technologies that are far from obsolete.			OC
24	Plan redundancies.			OC

***Principles ref. to the principles presented in section 4.1
 (CP = Reduce the effort of changing procedure, EC = Reduce the effect of changes,
 OC = Reduce the occurrence of changing the product)**

5. Discussion

A new approach was presented to develop products with a flexible architecture and design, so that the product can be adapted to new functions, when requirements are initially unknown and/or change during product development phase.

24 product development guidelines are collected from literature and supplemented with new ones, which were discovered during a practical project. These textual guidelines were evaluated in the same practical project and additionally tested in a laboratory study with engineering design students. The detailed results were already presented on ICED07 [Bischof 2007]. While the application of the guidelines subjectively supported the product development engineer without limiting the solution space and thus were rated as a useful tool the laboratory study led to less definite outcomes: Using the guidelines slightly more flexible products were developed. The students using the guidelines did less redesign in comparison to a group working without the guidelines, when new requirements were presented half way through the study. However, using the guidelines did was not significantly rated as a useful tool, good support and/or motivation in a product development project with uncertainty and changing requirements.

Here the guidelines are arranged in a new way and illustrations were added to the originally only textual guidelines to archive better understanding and higher acceptance. New evaluation studies have to be carried out in order to investigate, if product flexibility in the early phases of the development process is a useful approach to handle changing requirements. Future research also has to show, if the presented guidelines are a useful tool to create the intended flexibility.

6. Conclusion

In fast changing environments the systematic product development has to be extended from the classical approach as e.g. VDI 2221 [VDI 1993] or Ulrich/Eppinger [Ulrich 2003]. Flexibility is often proposed for product developing companies to stay competitive under these conditions. The development of flexible products is one form of the proposed flexibility. In this paper product development guidelines were presented, which can be used by product designers as a supportive tool to develop these flexible products.

The newly composed guidelines were already applied in a laboratory study and in a practical project. There are indications that the guidelines are a useful tool for the stated problem. In order to achieve more unambiguous results and create a better tool for the product development process the guidelines have to be revised. A first step to simplify understanding and remembering was taken by visualising the textual guidelines. It has to be investigated if this visualisation supports the product developers' work without restricting the solutions. Additionally the research will be continued in order to identify further flexibility guidelines to be integrated in the existing set. Due to the differing foci of the guidelines it will be important to define more precisely the areas of application.

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