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A close look on product flexibility

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Abstract
Different technical products are analysed in order to derive design principles and/or guidelines to support the development of flexible products. Thereby it is differed between products that can easily be adapted in case of external changes, namely flexible products, and products that do not have to be changed in case of external products, namely robust products. The analysis led to four design principles explicitly supporting the development of flexible products and three aiming at the development of robust products. These principles are formalized in guidelines. Moreover a plain model for understanding product flexibility is derived for the product analysis.

Keywords: Product design, product flexibility, robust products, detail design, design features.

1 Introduction
In fast changing environments flexibility is often mentioned as a basic necessity [1]. This flexibility incorporates strategic and management flexibility, flexible development processes, flexibility in production like flexible manufacturing systems (FMS) [2] as well as flexible products, which can easily be adapted to changed conditions during the product life [3].

1.1 Problem statement
There are many different tools (e.g. methods and guidelines) which support the development of flexible products [e.g. 4, 5, 6]. Most of them focus on one specific attribute of flexibility, like e.g. Design for Adaptability [5], Design for Changeability [6] and Design for Modularisation [7]. Even though different design guidelines are presented the support given by these is rather vague. General concepts which help to design flexible products, like modularization, are extensively explained. But on a detailed level, which becomes relevant in the embodiment design phase, most concepts are less precise and provide less support for the designer.

1.2 Motivation
For practitioners appropriate supporting tools have to be developed in order to better support the product design process. As an initial literature study did not lead to satisfying results a different approach is taken in this case: A lot of flexible products can be found. Sometimes it is difficult to say whether they were designed flexible due to specific requirements, to handle uncertain and/or changing requirements or other reasons. Independent of the reasons for why and when the flexibility was implemented we analyzed some products on a very detailed level, to understand what precisely makes them flexible. The gathered information is

structured and shall help in future development projects to show how to design implicitly flexible products.

1.3 Objectives

The idea is to understand how flexibility incorporated in a product is realized in detail. This understanding might be used to define a simple tool which supports the product developer when designing flexible products. For many cases design guidelines have been useful for engineers. They are easy to understand, learn and remember. Their application is simple. As they are less strict they allow interpretation and do not limit creativity. Thus here guidelines which support the development of flexible products will be developed.

1.4 Approach

In order to gain a better understanding of product flexibility different physical products are analyzed. Therefore products are decomposed either physical or mentally. The product flexibility is analysed on different levels: system, product, assembly, subassembly, part and feature. Within this analysis the focus is narrowed on “flexible areas” of the products instead of the whole product in order to limit the work load and to ease the examples. The detected characteristics of flexibility are clustered and compared between the different products in order to derive commonalities. These commonalities form the basis of product flexibility which is often cited but not jet described in detail. If this basis – the essence of flexibility – is detected, described and understood correctly it can be used in general to implement flexibility in all kinds of technical product for different reasons. Therefore it has to be transformed in a more useful tool to make it more applicable for future design tasks.

2. Flexible Products – State of the Art

Analysing existing technical products is a popular approach to understand product flexibility. Palani Rajan et al. worked extensively on the topic of flexible products [4]. They state that “it is clear that flexibility is highly dependent on the particular change in question. As a result, it is very difficult to discuss comparisons between vastly different products” [4]. Even though they postulate that “some products are clearly more flexible than others to redesign“ [4]. Examples might be the ones given by Palani Rajan et al. in table 1 [4].

2.1 FLEXIBLE PRODUCT Development vs. FLEXIBLE Product DEVELOPMENT

While the engineering and manufacturing capacity influence flexibility, here the focus is on the product itself as a reflection of flexibility. For example, some products are clearly more flexible than others to redesign. Table 1 gives five pairs of examples of products, which are relatively more flexible, when compared to counterparts [4]:

Table 1. Inflexible and Flexible product examples, after [4]

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

Remaining flexible

The idea of remaining flexible (in a generic sense) throughout a product development process (PDP) in a rapidly changing environment and thus remaining competitive was already proposed by Thomke and is still the focus of current research [1]. His work is on a more

general level: He and others do not propose guidelines or other practical tools for product developers. Instead he focuses on the importance of agile acting and reacting during the PDP [1] for designers and all other involved people within the company.
In short the idea of Thomke is to keep options open or to generate new options in order to act agilely when necessary.

Product flexibility

Many different terms as e.g. “flexibility”, “changeability”, “versatility” and “adaptability” are used in literature to describe similar, but not identical aspects of the PDP and properties of technical products. We understand in following the terms “flexibility” and “flexible” 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) to the design process [1].
Following this definition flexible products are here defined as products, which can be adapted to a changed environment – changed needs and requirements - with little amount of time and costs within the development phase as well as during the rest of the product life cycle (cf. fig. 1). Thus a product would contain highest flexibility, if it does not have to be adapted at all when changes in the product’s environment occur, because the new requirements are covered by the original product (cf. fig 1). Following other definitions these products are called robust products: Robust products are designed in order to make a product’s performance insensitive to raw material variation, manufacturing variability, and variations in the operating environment [8]. The basic idea of robust design was first evolved by Taguchi. It makes use of statistical experimentation planning methods in order to make the product design robust towards external tolerance deviation [9].

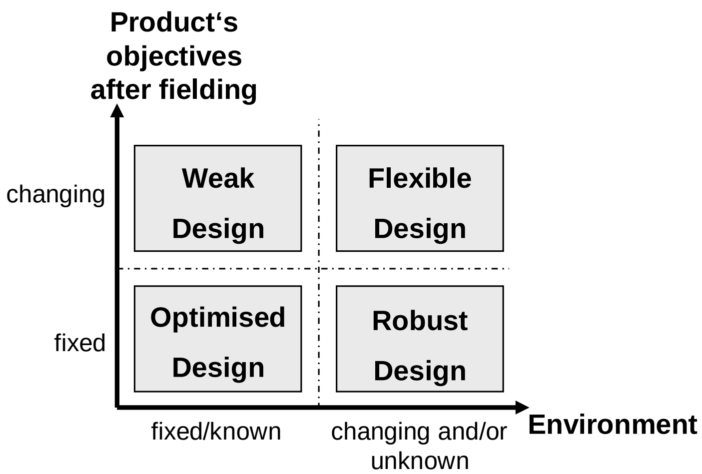


Figure 1. Product flexibility and robustness as a function of the system’s objectives and environment, after [10]

2.2 Different views on product flexibility

Often related research focuses 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.

Design for Flexibility

Palani Rajan et al. [4] 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 assessing product's flexibility analogous to Failure Mode and Effect Analysis. This so called Change Mode and Effects Analysis (CMEA) is a systematic approach to understand how future changes might affect a product. They also propose flexibility guidelines for designers to change a design based on the results from the CMEA. This approach is to design the product in a way that it can easily be redesigned to new requirements. Thus it partly includes the ideas of robust design, as robust products do not have to be redesigned at all in case of environmental changes [10].

Design for Modularisation

Modularity is a major issue in research on flexible products [e.g. 11]. Modular Function Deployment (MFD) as presented by Erixon [7] is one approach used to modularise a product in order to allow it to be changed more easily when changes occur during a PDP or to be adapted to new requirements in later phases of product life. Changes can be made within modules 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 modular structures and interfaces. Sosa et al. [12] 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.

Thus modularisation is an important aspect of flexible product design. By modularising the product the avalanche effect of changing the design is reduced and the changing procedure is eased. However, it is not the modularisation itself, but the loose coupling between the modules that enable uncomplicated changes, redesign and reconfiguration.

Flexible Product Platforms

The concepts of product platform and product architecture are strongly related to the modularisation concept. Hölltä-Otto defines a platform as the common set of physical or non-physical modules from whichmultiple products can be [13]. 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" [13].

In a simplified way behind (flexible) product platforms lies the same idea as of modular design. Assemblies, subassemblies, parts and modules can easily be changed, thus the product be reconfigured to the new requirements.

Design for Variety

Design for Variety (DfV) is another approach to design products to meet the diverse customer requirements [14]. The idea is to build a series of similar products based on the same product architecture. Martin and Ishii [14] quote Ulrich [15], 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 [13]. Van Wie [16] describes a systematic method for creating an 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.
In contrast to "flexible design" in the way of Palani et al. the design DfV is more focused on the architecture of the product. The architecture has to be developed in a way that form the same "backbone" a suitable variety can be derived. Later changes of single components are usually not intended.

Design for Changeability

There are different interpretations of the concept of Design for Changeability (DfC). While Schuh et al. [6] focus on the flexibility of the production process and its machinery, Fricke et al. present different "principles to enable changes in systems throughout their entire life cycle" [17]. As products are part of systems and can have a comparable high complexity, the distinction between products and systems is neglected in this paper 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.
By including the four different aspects of changeability the DfC approach aims at robust design (viz. not changing the product at all) and at flexibility (easy to change) at the same time. Especially in sense of Schuh the DfC approach aims at easing the changing procedure itself.

Design for Adaptability

Design for Adaptability is presented by Hashemian with a focus on the extended utility of products [5]. 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.
In this sense the DfA approach does not differ much from the DfF approach. But it is more focused on the later phases of product life (viz. to ease changing effort for the customer), while DfF may also be advantageous in the development phase of product life.

3. Analysing flexible products

Like most of the other approaches the DfF and DfV approaches are derived form product analyses. When analysing product flexibility with the Change Mode Effects Analysis (CMEA) several product development and design guidelines were derived. These guidelines are proposed for future product development in order to improve product flexibility [16]:

1. Improve the design flexibility by making the device more modular.
2. Reduce the effect of a change in a design by increasing the number of partitions. This will lessen the impact of any individual element on the whole if a change becomes necessary for the element in question.
3. Reduce the effect of a change by increasing the number or size of virtual or actual buffer zones.
4. Reduce the occurrence of a change by increasing the performance envelope of the device
5. Reduce the occurrence of changes by standardizing components and interfaces.

6. Reduce occurrence of changes by selecting technology which is far from obsolescence.

Even though Van Wie's underlying product analysis was extensive [16] in this paper, the focus is on deriving more detailed design guidelines for product flexibility based on Van Wie's ideas. The focus is especially on the part and feature layers, as these are the ones that can be influenced to the responsibility of a single designer.

3.1 Products analysed

For the analysis different products have been chosen. The nine products listed below define a wide range of technical products, but the focus is on consumer goods:

- Drilling machine
- Basis platform of tool machine
- Computer server rack
- Camper van table
- Sofa bed
- Office chair
- Bicycle
- Headphones
- Puncher

The products were chosen randomly to show that flexibility can be identified in almost every product.

3.2 Analysing method

Such as the first step of the CMEA method the products are decomposed physically or mentally. The decomposition is done with respect to product-, assembly-, subassembly-, part- and feature-layer. The two layers environment and function were additionally included, because some products are flexible in their main functionality and in some cases their flexibility is only understandable with respect to the product environment.

While older studies mainly analyse products on a generic level [1] or focus on the functional layer [5] the focus of this analysis is on the part and feature level. This is the level which can be influenced by almost a single designer. The system layer and the product (architecture) layer are usually affected by superior requirements. These superior requirements can be company internal (e.g. fixed manufacturing capabilities), external (e.g. market demands), product specific (e.g. specific technical aspect like weight limitation) and in consequence of the environment (e.g. "to be used under water").

3.3 Product layers

As described above the products' flexibility was analysed on different layers. These layers are defined as described in the following paragraphs:

Product layer

The product is something sold by an enterprise to its customers [15]. For the analysis the focus is limited to products that are engineered and physical. On the product layer the product is understood as a whole. The flexibilty is analysed regarding the main function and regarding the assembled product, not taking into account the flexibilty on the inferior layers.

Assembly layer

As products can be quite complex, viz. consist of many parts, they can be divided into assemblies and subassemblies. These assemblies are defined as number of part mounted together to one unit. In this sense it differs not from a module. In our understanding a module is bigger, and usually defined by functionality, while assemblies are derived from the assembly process and physical alignment of assembled parts.

Part layer

A part is one single object. It is not possible to disassemble it any further. In this sense not dismountable assemblies are defined as pars (e.g. welded constructions like bicycle frames). In the product analysis it is searched, if there is flexibility inherent in the part to be identified.

Feature

According to the Cambridge Dictionary a feature is defined as “a part of a building or of an area of land” [18]. In the technical area it is one functional area of a part, e.g. thread on a screw.

Function

According to the definition of Pahl/Beitz [19] the term function is used to describe the intended input-output relationship of a system whose purpose is to perform a task.

Environment

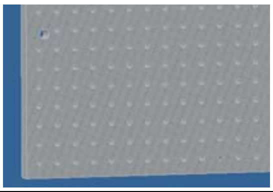
The term environment is used in sense of a non technical context the product is placed in.

4 Results - detected product flexibility

In table 2 the product inherent flexibility is shown. Due to limited space not all results can be presented here. But the selection of the examples given in the table shows the wide range of products, the wide range/understanding of flexibility and the fact that in line with the given definition of product flexibility (cf. sec. 2.1) principles that enable product flexibility can be found on every layer (respectively on every product abstraction level).

Table 2. Product flexibility in reference to specific product layers

Product	**Description**	
Bicycle 	Environment: Assembly/Module: Subassembly: Part: Feature:	easy to carry, *lightweight design* seat+post, *seat height continuous adjustable, linear sliding movement* drivetrain, *transmission stepwise adjustable* rear derailleur, *continuous linear+rotating movement* saddle, *lengthwise adjustability* slide rail
Hand drilling machine 	Environment: Function:	easy to carry, *accumulator - autonomous power supply* hand drilling machine hammer drill cordless screwdriver, *three main functions provided by switching on/off specific functions (hammer), offering continuous adjustability (speed control, tool fitting)*

	Subassembly:	rotation speed control, *continuous adjustable* tool fitting, *continuous adjustable*
	Part:	press button, *linear sliding movement* *radial sliding movement*
Basis platform of tool machine 	Feature:	grid layout for tapped bores, multiple/*redundant use of same feature, standard interface to enable mounting of equipment in different directions and positions*
Server rack 	Part:	slider, *asymmetric layout allows two ways of installation*
	Feature:	slot hole, *for angle adjustment*
Caravan table 	Product:	*flexibility achieved by providing two functions and by collapsibility*
	Function:	table/bedstead, *two main functions provided by one product enabled by two states*
	Subassembly:	collapsible mechanism, *rotation movement of table-leg, no part has to be removed*
	Part:	table-leg, *material inherent flexibility/elasticity is used to support stability of locking mechanism in two positions* slide rail/joint, *no stopper, consciously adjustable in vertical direction*
Sofa bed 	Function:	sofa/bed, *two main functions provided by one product enabled by two states*
	Subassembly:	*continuous linear+rotating movement, fixed in two positions*
Office chair 	Assembly/Module:	seat height adjustment, *linear movement, fixable in every position* backrest, *angle adjustment*
	Subassembly:	piston, *linear movement*

Headphones 	Assembly/Module: Part:	ear cup, *elasticity of material used to provide "one size fits all" functionality* holder, *elastic band is used to adjust holder to head size* inner part ear cup, soft shell, *elasticity of material used to provide "one size fits all" functionality* elastic band, *elasticity of material used to provide "one size fits all" functionality*
Puncher 	Product: Part:	*"one size fits all" design* distance piece, *linear sliding movement allows adjustment to paper size*

5 Deriving commonalities

Based on the results of the product analysis we tried to derive common principles of flexibility that are detected within the products. Following the distinction of Saleh [10] the principles are divided into principles for the development of products that are easy to be adapted to as a reaction to external changes, i.e. flexible products, and for the development of products that are insensitive to external changes, i.e. robust products.

5.1 Common guidelines/principles for flexible product

In order to support the development of flexible products following principles are proposed. They all aim at reducing the time and/or cost of changing the product:

1. *Allow temporary rotation (fixable);* flexibility (viz. changing the product) is usually achieved by physical changes, if the physical change options are inherent in the product, time and cost for the change procedure are reduced.
2. *Allow temporary linear movement (fixable);* flexibility (viz. changing the product) is usually achieved by physical changes, if the physical change options are inherent in the product, time and cost for the change procedure are reduced.
3. *Provide different physical layouts/number of physical states (with a fixed set of parts);* realising different physical layouts/states within one usually allows easy (fast and cheap) changing one form to the other.
4. *Plan easy move ability/eased transportation;* in relation to its environment products are considered more flexible if changes within the environment (generally relocation) are eased.

The first two principles can more easily be implemented on the part and feature layer. But physical movements can be implemented on the assembly and product layer as well. In an abstract interpretation the fourth principle is a combination of the principles 1. and 2. on the environmental layer.
The third and fourth principles affect more the whole product and its relation to the environment. Thus, these two principles can be used more easily on the environmental and part layer than on the more detailed assembly, part and feature layers.

5.2 Common guidelines/principles for robust products

Besides the principles which enable the development of flexible products the analysis showed as well three principles we propose for the development of robust products:

5. *Integrate different/more than one temporary main function integrated in one product;* including different functions in one product reduces the probability of need for adapting the product when external factors (e.g. requirements) change (example: sofa bed).
6. *Plan redundancies;* this principle aims at offering different options (for the user): even when external factors change (e.g. other mounting needed on the basis of the tool machine) there is no need to redesign the product.
7. *Use elastic materials;* using the material inherent flexibility reduces the probability of changes, as the product adapts itself (within limits) to external changes.

As the principle proposed by Van Wie [16] (cf. sec. 3.) the principles 5. and 6. aim at "over engineering" the product. The seventh principle is based on a new idea: The flexibility offered by certain materials is used instead of using a specific design to make the product flexible viz. robust.

6 Discussion

Six new development guidelines/principles for the development of flexible products could be derived form a product analysis. Still the results are not satisfactory for different reasons: only a few products were analysed, the products do not represent the whole spectrum of technical artefacts, the detected flexibility is more in the use phase of the product life cycle than in the earlier phases (were it might be a bigger benefit for the company). The application of the principles has still to be evaluated. However, based on the results a new plain model of product flexibility, described in the next subsection, was developed.

6.1 Proposing a new model of product flexibility

Flexibility is similar to indeterminacy. But in contrast to unintended indeterminacy, which is consequence of uncertainty flexibility is planned and temporarily (cf. fig. 2):

Figure 2. Correlation of uncertainty, indeterminacy and flexibility

Thus flexibility is planned and temporarily indeterminacy. For example the bicycle seat post can be adjusted in its height by performing a continuous linear movement. So far it is flexible. At the favoured height it can be fixed. The temporarily indeterminacy finally is eliminated when using the product. Indeterminacy can also be found within the other products like the basis platform of the tool machine. Offering many possible mounting positions the basis can be considered (temporarily) over determined. When the tool/part is mounted for use the whole system is determined correctly.

Proposing new design guidelines to achieve product flexibility

As already mentioned, present development guidelines for flexible products aim mainly at two ideas: First, over engineering, and over sizing supports the development of robust

products. Second, developing with a high modularity the products are less sensitive towards external changes.
Here the idea is to present additional principles which support the development of flexible products. Three aspects of the new principles (cf. sec. 5) are new. The product analysis included the products environment. In our point of view this is important as usually products do not only fulfil a specific function but are in interaction with their environment. Moreover the principles differentiate explicitly between robust and flexible products. The third aspect is that it was especially tried to derive guidelines for the part and feature design, as these are the ones to be most influenced by a single designer.

7 Conclusion and further research

A brief product analysis led to a better understanding of product flexibility and robustness. A plain model of this flexibility (and robustness) is formulated in order to describe a new view on product flexibility.
For the development of flexible (and robust) products a few design principle/guidelines are derived. Even without implementing theses principles they can help the product developers to better understand product flexibility/robustness and thus sensitise them for reaction of the product in case of future changes. This might help to create more appropriate products.
Future research will be a more comprehensive product analysis in order to define more precisely guidelines to support the development of flexible products. A more comprehensive study can as well lead to even more applicable tools e.g. a catalogue with flexible design features and solution.
The second aspect of future research will be about the effect of flexible product design during the development process. The main question on this topic is if there is a benefit of developing flexible products already in the development phase, e.g. to reduce the number of iterations during the development process.

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