Master Thesis

Impact of Product Design on Agile Manufacturing

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Statutory Declaration

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Abstract

Production companies are facing nowadays an increasingly diverse and volatile environment. Through enhanced agility thinking, firms are able setting proactive measures to support later changes. During the product development process, the product design is an important stage that can help prepare for these uncertainties. Therefore, this thesis aims at determining the influence of different design concepts on agile manufacturing.

Through a literature review, main design concepts are gathered and categorised. By combining the main guidelines of different design approaches, a design catalogue is created. Following this, an academic evaluation is conducted on the catalogue in order to determine the main levers to influence different agility drivers.

In order to evaluate which concepts are used within the industry, interviews with experts of several production companies are conducted. Furthermore, the applicability of the design catalogue is evaluated.
Three case studies on specific products deepen the investigation of the design catalogue to combine the external with the academic evaluation. This illustrates the potential improving the product design in order to react more accurate to different agility drivers.

Acknowledgement

I would like to thank to all the people who helped and supported me during the accomplishing of this master thesis.

At first, I would like to express my deepest appreciation to my supervisor Mr. Alexander Pointner, who continually supported me with his knowledge. Furthermore, he helped me with his business contacts in order to find suitable experts for my interviews.

Furthermore, I would like to thank the interview partners from the different companies. Due to their input and help it was possible to include their years of experience from the industry into the thesis.

In addition, I would like to express my warm thanks to all research assistants and diploma students for their evaluation of my work. With their help my design catalogue got improved and matured.

Lastly, a thank you to my friends and my family, who supported and encouraged me on continuing with the thesis during hard times. With their positive words I always found further motivation for the work.

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1 Introduction

Since the last few years, companies have to deal with increasing volatility. It is more difficult to rely solely on the forecasts as sales fluctuations are more unpredictable and therefore more difficult to handle. Instead of a constant production volume after the product release, companies are facing sales jumps.[1]

Furthermore, the variety of products has been increased tremendously in the last decades. The consultant company Roland Berger announced 2012 a study about the average number of sales products of the automotive, chemical, machinery, fast moving consumer goods (FMCG) and pharmaceuticals industry. The outcome was that the number of sales increased to around 220 per cent between 1997 and 2012 (Figure 1).[2] Furthermore, they present a forecast, which shows a similar increase after the following years. The smaller increase of raw materials and components results of an increasing focus on standardization and modularization since around 2002.

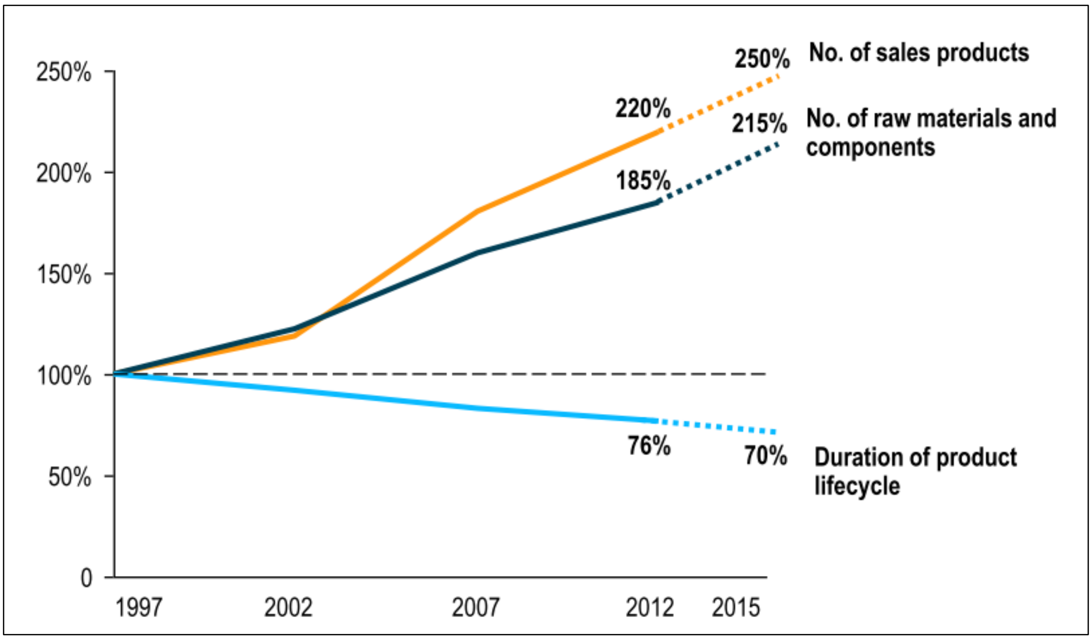

Figure 1: Trend of Product Variety and Product Lifecycle[3]

[1] c.f. Wiendahl *et al.* 2007, p. 783

[2] c.f. Roland Berger Strategy Consultants 2012, p. 5

[3] Roland Berger Strategy Consultants 2012, p. 5

At the same time the product life cycle decreased from 100 to 76 percent.

Looking more specifically into the engineering industry, similarly discoveries can be made (Figure 2). Whereas in the automotive sector the product variety have been increased in the same period from 100 to 170 percent the increase of the raw materials and components are significant lower. The authors of the survey declared that early standardization and modularization approaches is already matured within this sector.
In comparison in the common machinery industry the increasing of part number is nearly equal to the increase of sales products. In this area modularization and standardization is not established at the same degree as in the automotive sector.

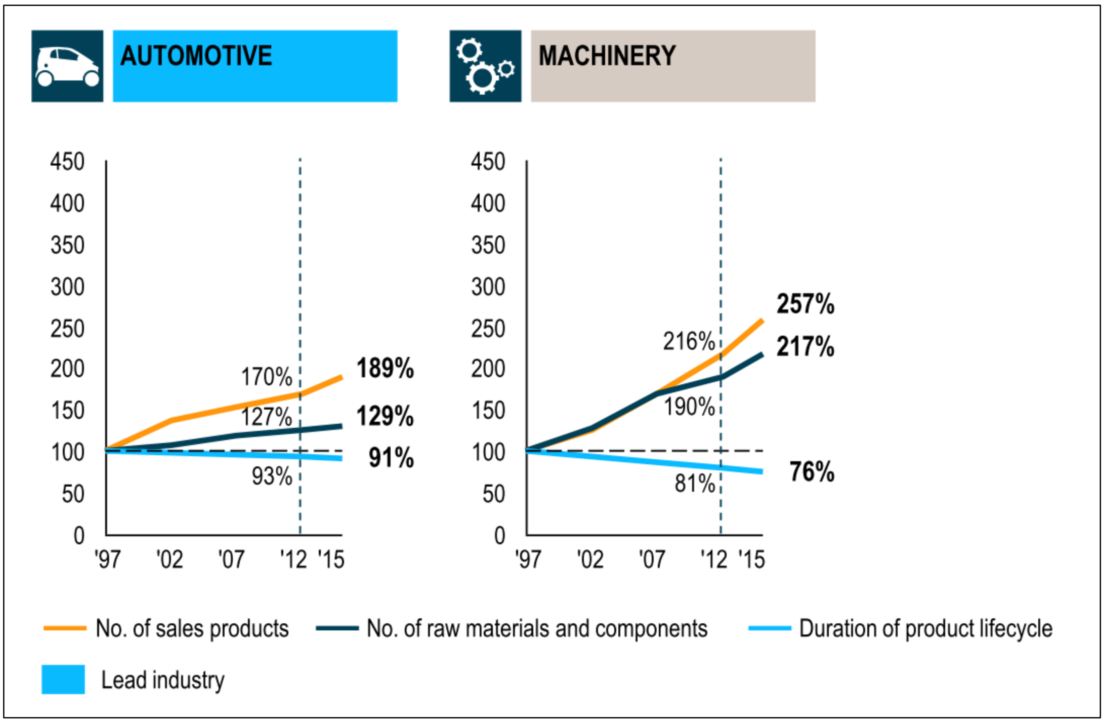

Figure 2: Increase of Product Variety in Discrete Industries[4]

This increase in combination with the unpredictable view into the future lead to the requirement for companies to prepare for these events. Agility is an approach to improve a company's capability to react in a more efficient way to these changes.[5]

[4] Roland Berger Strategy Consultants 2012, p. 9

[5] c.f. Schurig *et al.* 2014, p. 956

1.1 Initial Situation

For a company there are several ways to increase the agility within their company.

One approach is to focus on the product design stage within the product development process. Anderson describes that roughly 80 per cent of a product is already determined after designing the product whereas only 10-15 per cent of the costs actual incurred (Figure 3).[6]

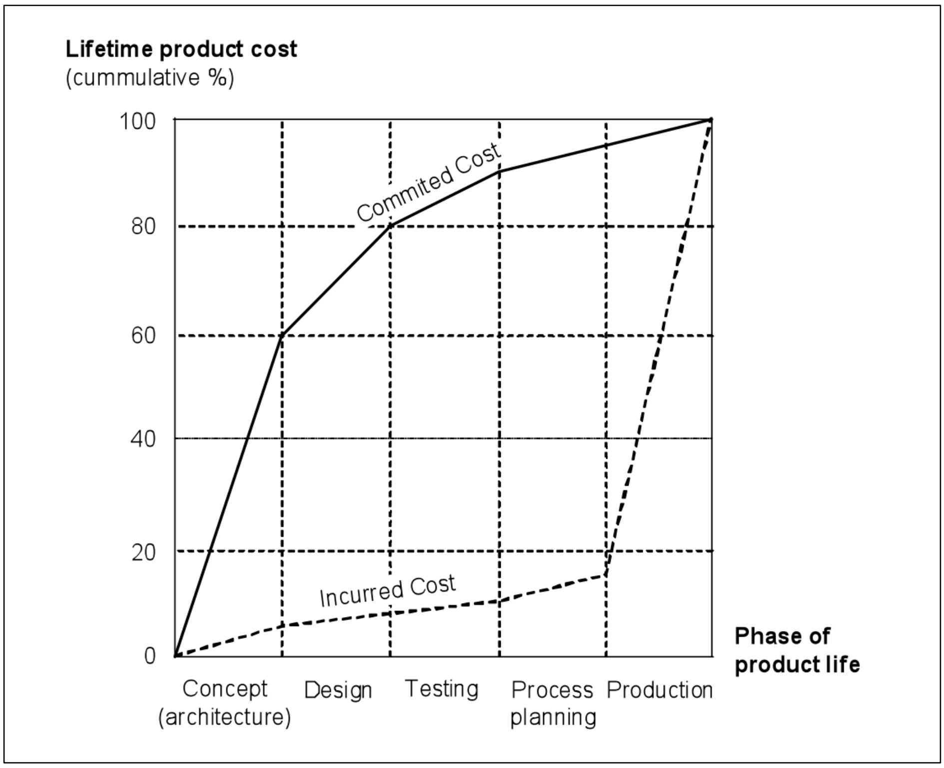

Figure 3: When Cost is Determined[7]

This observation lead to the necessity to investigate product design concepts, which can be used within the design stage, in order to influence the agility. The purpose of this thesis is to illustrated, which concepts have the most effect to react to changes in a more efficient way.

[6] c.f. Anderson 1997, pp. 131–133

[7] Anderson 1997, p. 132

1.1.1 Cost of Changes during and after Product Design

The importance of a well-defined product design is crucial to achieve a high level of quality. If changes occur after the product design phase it can be very cost-intensive for the company. Boehm pointed out that the factor, by which the cost of changing software exponentially rises from the requirement phase to the operation phase, is roughly 100.[8] Although applied to the software industry, it outlines the importance of avoiding late changes.
Another cost of changes approach is provided by Anderson. He stated that after every product development process step the cost is rising by a factor of 10 (Table 1). He defined this phenomenon as the 'Rule of Ten'. After every assembly step the cost of finding and repairing the defect is 10 times higher than the assembly step before.[9]

Table 1: Cost of Engineering Changes[10]

Time of Design Change	Cost
During design:	$1000
During design testing:	$10,000
During process planning:	$100,000
During test production:	$1,000,000
During final production:	$10,000,000

Smith warns that these rules have to be considered very carefully, it is just a basic signal that changes after the design stage can be very cost-intensive.[11]
Although the approaches have a limited applicability within different industry, it demonstrates the importance of a well-defined product design in order to reduce the cost which otherwise product changes cause.

1.2 Objectives

As discussed before, late changes can be very cost-intensive. Therefore, it is the goal of this thesis to find concepts, which support changes at a later development phase.

[8] c.f. Stecklein *et al.* 2004, pp. 1–2

[9] c.f. Anderson 2014, p. 309

[10] Anderson 1997, p. 139

[11] c.f. Smith 2007, pp. 8–10

Furthermore, as during the product design stage the main production costs of the product are determined, the right selecting of manufacturing processes and materials supports on the one hand cheaper fabrication, on the other hand supports agile manufacturing.[12]

Splitting this complex topic into several sub-goals following objectives have been formulated:

(1) Overview of concepts during the product design stage to influence agile manufacturing

(2) Evaluation of the concepts concerning agile manufacturing

1.3 Approach

Derived from the above described goals, the following approach to cover the major topics is developed (Figure 4).

At first, to get a better understanding of agile manufacturing, agility and the major goals behind that approach a detailed literature review is carried out. Furthermore, design concepts which are described in the literature, in combination with agility are collected and categorised.
Following this, a design catalogue is formulated which serves as a basis for further investigation. This catalogue includes main guidelines from different product design concepts.
After that, an internal evaluation of the design catalogue assesses the main concepts to influence agile manufacturing. For that reasons, the changes, which are the need for agility, are divided into design changes and demand fluctuations.

To evaluate which concepts are already used and how important agility within the industry is, several expert interviews with companies are carried out.
The last point covers case studies for further investigations of the design catalogue. It will be clarified if the catalogue can support a company's agility.

[12] c.f. Lee 1998, p. 1024

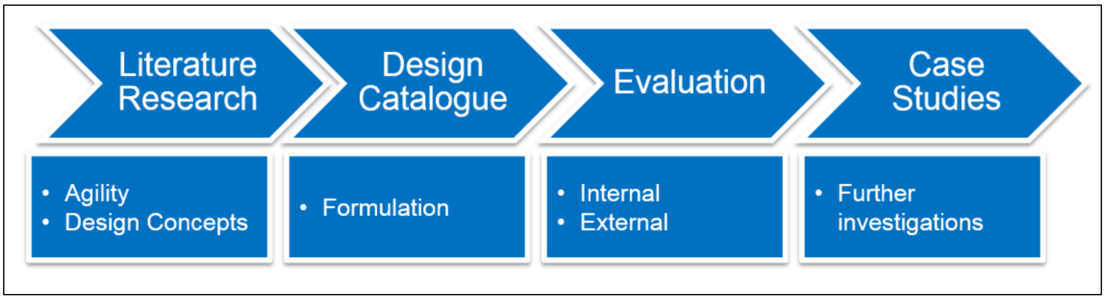

Figure 4: Approach

2 Principles about Product Development and Agile Manufacturing

In this chapter a general overview on the topics product development process, product architecture and agile manufacturing is provided.
At first the product development process, which is the overriding process of product design, is explained. Special variants of the traditional process are further described in detail.
The next part contains the structure of a product, which is often called product architecture. The division into modular and integral design helps to distinguish between the two main options of product architecture.
A short summery of standardization is given, which is a general approach within the product design and other stages to reduce variants and simplify parts as well as processes.
The last part deals with the topic agility. Several definitions of agility and the influenced area within a company are provided. Furthermore, it is outlined how the lean approach influences the agility.
A conclusion sums up the main literature topics and explain on, which topics focused in this thesis will be on.

2.1 Product Development Process

A product undergoes several stages during its life cycle. At the beginning of such a cycle the product concept has to be defined, the actual design is developed and tested. The sum of these stages is called product development process (PDP).[13] The traditional PDP is mainly divided into product development and production preparation.[14] Nowadays, highly innovative companies are more concentrating on the new product development process, which focuses on narrowing the possibilities of products in order to select the right product during the development process.[15]

[13] c.f. Westkämper 2006, pp. 117–118

[14] c.f. Eigner and Stelzer 2009, pp. 1–2

[15] c.f. Cooper 2001, pp. 50–51

In this chapter the traditional, the new product development process as well as some specific product development process are described in detail.

2.1.1 Traditional Product Development Process

In literature different approaches to define and allocate the single stages of a traditional product development process are available.
Eigner and Stelzer use the stages requirements, product planning and part of the design process to define the product design stage whereas part of the design and mainly the process planning describes the production preparation stage.
The combination of product design and production preparation is described as product development process (see Figure 5).[16]

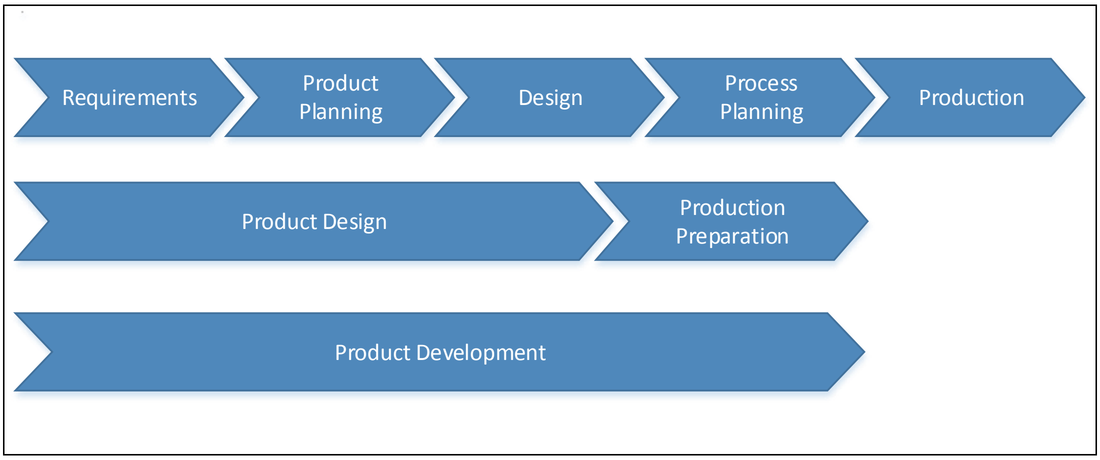

Figure 5: Relation of Product Design, Production Preparation and Product Development. Own Representation based on Eigner and Stelzer 2009[17]

Westkämper divides the whole product development process directly into research, product planning, product design and prototype testing. He allocates the production preparation to the production process (see Figure 6).[18]

[16] c.f. Eigner and Stelzer 2009, p. 2

[17] c.f. Eigner and Stelzer 2009, p. 2

[18] c.f. Westkämper 2006, pp. 117–119

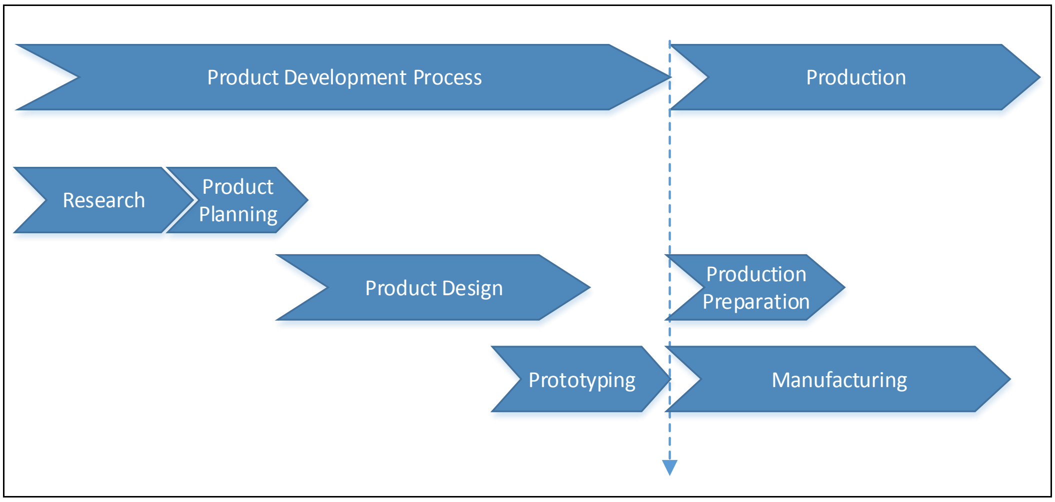

Figure 6: Product Development Phases. Own Representation based on Westkämper 2006[19]

2.1.2 New Product Development

Highly innovative companies use a more specific approach, which is called new product development (NPD). The goal of this process is to screen through the amount of product ideas at the beginning of the product development process and to concentrate on the most promising product during the developing.[20]

Cooper developed the "Stage-Gate Process", in which the whole NPD process is divided into five stages, scoping, build business case, development, testing & validation and launch.
After each stage the progress of the development is being checked and evaluated at each gate (Figure 7).[21]

[19] c.f. Westkämper 2006, p. 118

[20] c.f. Cooper 2001, pp. 50–51

[21] c.f. Cooper 2001, pp. 129–131

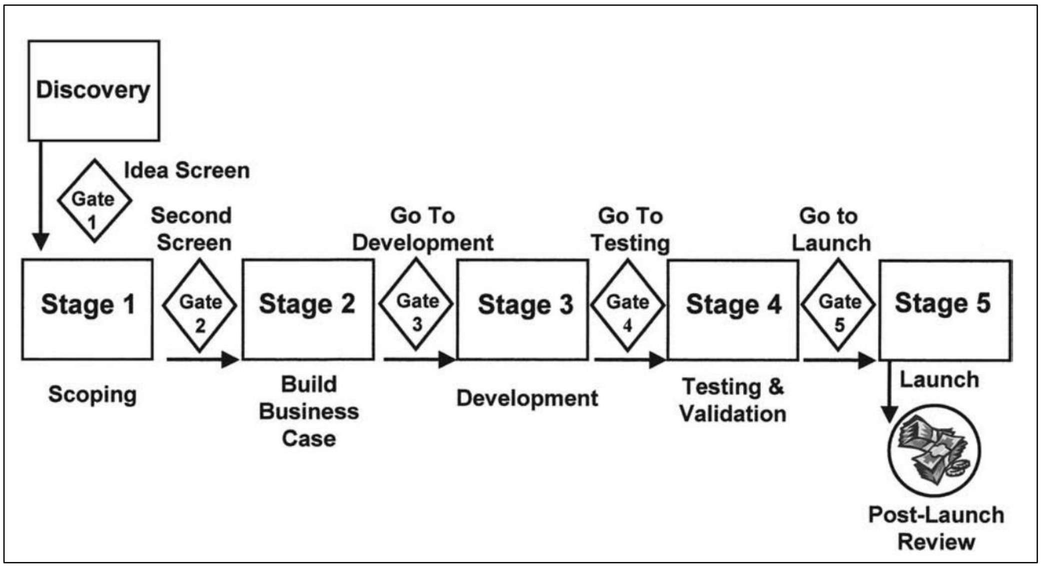

Figure 7: A Stage-Gate Model- From Discovery to Launch[22]

2.1.3 Further Product Development Processes

For specific areas, e.g. the automotive sector, the traditional PDP has been adapted to the present requirements.
Especially, in the automotive sector it is common to introduce milestones, which track the progress of the development process.

Göpfert describes in his approach four stages with in total twelve milestones, in which the product development starts after the mile stone target catalogue. (Figure 8)
The original equipment manufacturer (OEM) in the automotive sector and all automotive supplier derive their individual product development process and milestones from that theoretical approach.

Another approach to illustrate the product development process, which is also used in the automobile sector, is the so called "V-Model". In this model, the development process is split into a downward and an upward development (Figure 9).
In the downward movement the whole vehicle specification is broken down into system and part specification. When the components are designed and

[22] Cooper 2001, p. 130

evaluated they are integrated to a whole model, which represents the upward movement. The testing is done in hierarchical order, from parts over assemblies up to the whole car. Prototypes have an own individual V-Model.[23]

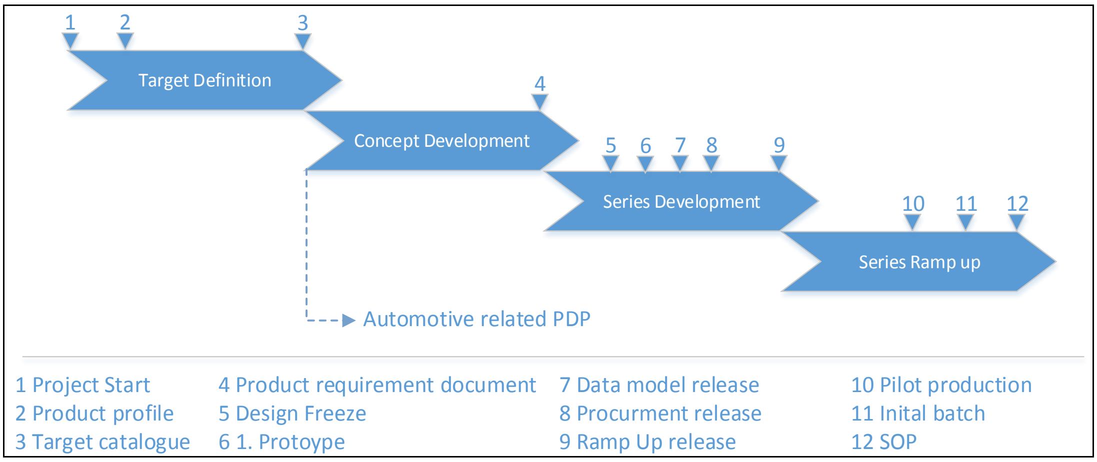

Figure 8: Product Development Process with Milestones. Own Representation based on Göpfert 2012[24]

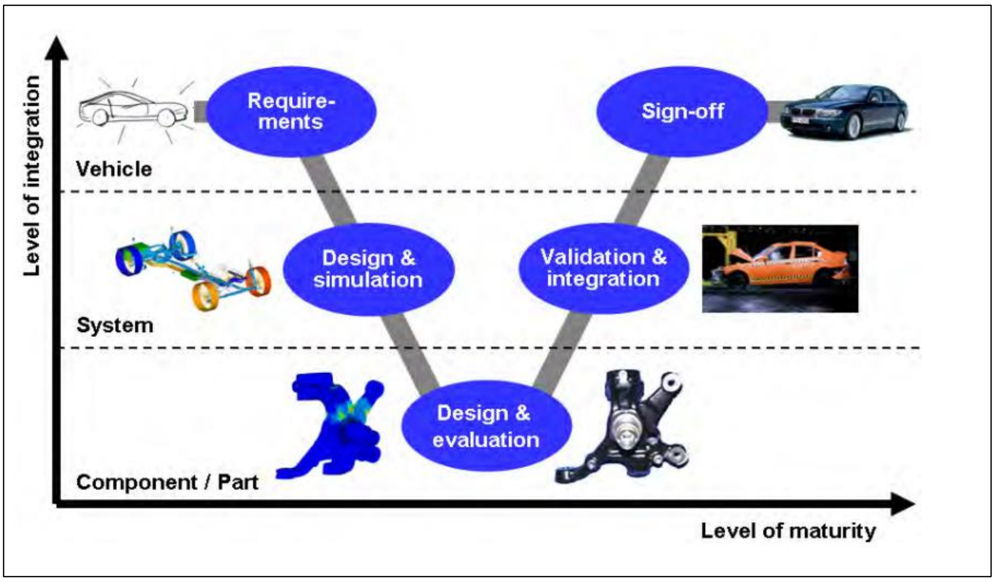

Figure 9: Application of the V-Model[25]

[23] c.f. Weber 2009, pp. 11–12; c.f. Otto and Wood 2001, p. 39

[24] c.f. Göpfert 2012, p. 245

[25] Weber 2009, p. 11

2.2 Product Architecture

At an elementary level, each product needs an architecture, which defines the structure. A product architecture has the aim to define the layout of the product, furthermore it has a huge influence on the design process of the system and further on the subsystems.[26]

Ulrich defines product architecture as:[27]

1. “The arrangement of functional elements“
2. “The mapping from functional elements to physical components”
3. “The specification of the interfaces among interacting physical components“

From this definition two main architecture types can be derived. The first is an integral architecture whereas the opposite is a modular architecture. It is crucial to define both before designing a product.[28]

2.2.1 Integral

Integral product architecture are systems, in which individual physical elements, so called chunks, are not separated from each other. This means that these chunks in a product have no defined interface, instead they are blend together at the interfaces. They contain and carry out several functions.[29]
Integral design is often applied at simple products or assemblies which have a high production quantity. This architecture helps to reduce the assembly effort by reducing the number of parts and increase the function sharing.[30]
Examples of integral design are e.g. screwdrivers, knives or vegetable peelers.

[26] c.f. Otto and Wood 2001, pp. 359–360

[27] Ulrich 1995, p. 420

[28] c.f. Smith 2007, pp. 58–59

[29] c.f. Otto and Wood 2001, pp. 360–361; c.f. Smith 2007, p. 59

[30] c.f. Otto and Wood 2001, pp. 360–361

2.2.2 Modularity

In comparison, modular design focuses on dividing a product in physical elements with defined interfaces. The physical elements have a one-to-one relationship with the product’s functional model. The goal of a modular design is, that specific chunks should fulfill defined functions so these chunks can be replaced or new ones can be easily added.[31]

Otto and Wood define two kind of macro modular types, function-based and manufacturing-based modularity. Function based modularity splits up a product’s functionality whereas the manufacturing based modularity helps the production department to manufacture or assembly a complex product more easily.[32]

Ulrich further divides functional modularity into ways how the subsystems interact with each other:[33]

- Slot modularity describes modules, which have a basic device with which all others are connected. The interfaces between the linked subsystems are different and cannot be swapped. An example of slot modularity is a radio in a car.
- Bus modularity has similarly one basic component, but this component acts as a standard interface to other modules. Therefore, units, which have the same connection, can be added. A basic example is a shelve system, which has common rails.
- Sectional modularity is a system where all subsystems have the same interface but no central device. Lego® is a basic example of sectional modularity.

Figure 10 shows the different functional modularity concepts on the example personal computer.

[31] c.f. Ulrich 1995, p. 422; c.f. Otto and Wood 2001, p. 361

[32] c.f. Otto and Wood 2001, p. 364

[33] c.f. Ulrich 1995, p. 424

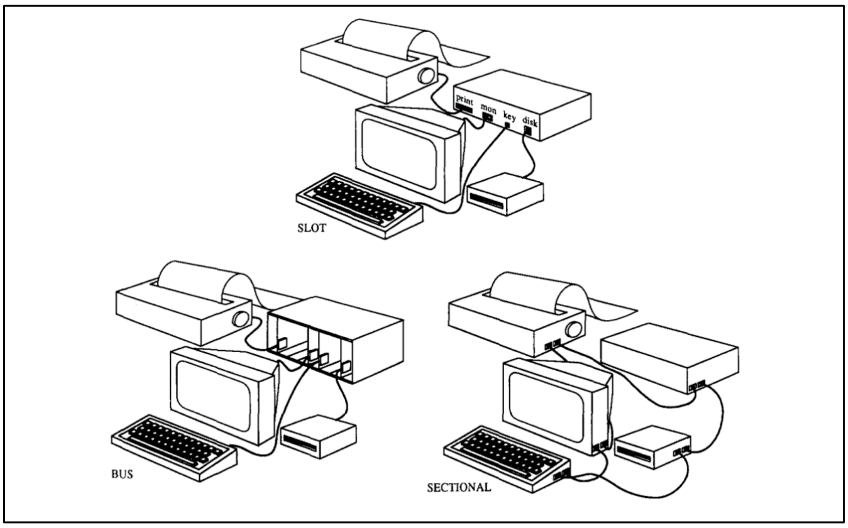

Figure 10: Different Functional Modularity Examples[34]

Otto and Wood added mixed modularity to Ulrich`s definition. They noted that all kind of functional modularity could be combined in one product. Examples would be complex products, like helicopters or cars.[35]

Manufacturing-based modularity is an additional way to divide modularity with respect to production.[36]

- OEM (Original Equipment Manufacturer) modules have the advantage that a supplier is able to provide components cheaper than developing and testing them again in-house.
- Assembly modules include parts or group of parts, which usually have different independent functions, but for the ease of machining or mounting they are grouped together.
- Sizable modules have no difference in function or main design just the physical dimensions of the modules are different. Therefore, manufacturing operations are the same for the different modules.
- Within conceptual modules the functionality of the unit is the same but the physical implementation is different. The design can be changed without affecting the functionality of the product. Nevertheless, it is

[34] Ulrich 1995, p. 426

[35] c.f. Otto and Wood 2001, pp. 365–366

[36] c.f. Otto and Wood 2001, pp. 366–369

generally attempting to standardize these modules in order to increase quantity and reduce developing effort.

2.2.3 Platform

Platforms are a specific application of modularity and are used within a range of similar products. McGrath defines product platform as “a collection of the common elements, especially the underlying core technology, implemented across a range of products.”[37]

Otto and Wood classify the platform architecture further:[38]

- Modular product families use identical units at the same generation along different products.
- Whereas modular product generations share unchanged modules along products, which are released at a later time or which are updates of the previous ones.
- Scalable platforms share parts, which are the same, except of the size. This kind of platform is related to the previous mentioned classification of sizable modules.
- Another version of platforms are called consumable platforms. Herewith, units are designed for usage.
- Standard platforms have subsets which are universal applicable within the industry due to an agreed standard.
- The last platform classification is adjustable to purchase assemblies. These are subsets, which have the goal to serve different clients in different market.

The benefits of using platforms for companies are a result of using parts and assemblies in more products. Fewer individual units reduce system complexity, the production costs as well as the developing time and cost.
Product variety can be easier realized, a company’s flexibility is increased and the risk is decreased by less investment costs.
Furthermore, the learning process within complex products is supported as well as validation and certification is simplified.[39]

[37] McGrath 1995, p. 93

[38] c.f. Otto and Wood 2001, pp. 308–312

Especially in the automotive industry platforms are widely used. By using underbody models in several car models individual cost and time intensive developing can be reduced as well as plant efficiency will increase. A well-known example is the PQ34 platform from Volkswagen, which describes the arrangement of the engine related to the longitudinal frame and in which car model and generation the platform is used.[40]

The possible disadvantage of using platforms is the similarity of the products. It has been criticised that the difference between premium and cheaper brands is being declined.[41]

2.3 Standardization

Due to the todays' demand of huge product variety companies are faced with extensive part increase. To reduce the internal variety, standardisation of parts and process are used to decrease complexity and increase efficiency.[42]

Anderson divides standardization into five main categories to describe the affected areas:[43]

- Part Commonality
- Tool Commonality
- Feature Commonality
- Raw Material Commonality
- Process Standardisation

Ulrich distinguishes part communality further and splits up the standardization into internal and external. Internal standardisation focuses on parts, which are developed and produces in-house, whereas external

[39] c.f. Robertson and Ulrich 1998, p. 20

[40] c.f. Simpson *et al.* 2006, pp. 4–5

[41] c.f. Simpson *et al.* 2006, p. 5

[42] c.f. Anderson 1997, p. 92; c.f. Perera *et al.* 1999, p. 109

[43] Anderson 1997, pp. 109–116

standardisation covers standard and catalogue parts, which are purchased from suppliers. [44]

The standardization of expensive similar parts, which are purchased from suppliers, offers a huge opportunity to reduce costs. Anderson outlines that instead of buying just the right product, oversized products, which can be bought with higher quantity, lead to a greater economy of scale. Due to purchasing leverage and overhead savings, the price of the purchased product is declined. Some of the original sized product will still be cheaper but in average the costs are decreased (Figure 11).[45]

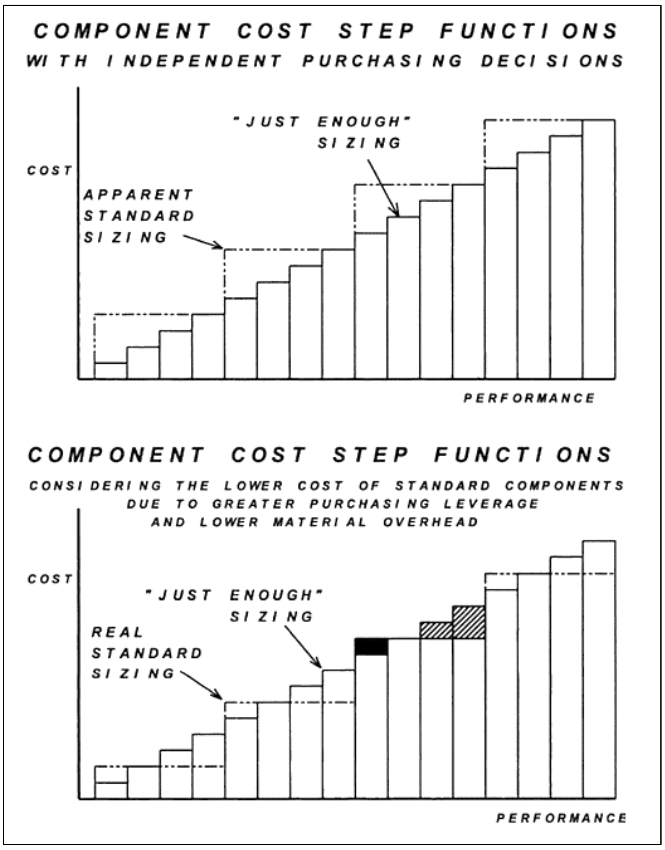

Figure 11: Standardization of Expensive Parts[46]

[44] c.f. Ulrich 1995, p. 431

[45] c.f. Anderson 1997, pp. 116–118

[46] Anderson 1997, p. 117

2.4 Agility

At first some different definition of agile manufacturing is provided, followed by further terms, which focus on reacting to changes. After that, it is investigated how the approach lean is influencing agility. Agility has in this thesis the same meaning as agile manufacturing.

2.4.1 Definition

Researches use different approaches to define the term agility within a company.

The first main concept was coined by a group of researches in the USA in 1991. The term agile manufacturing enterprise was developed with the main idea that an agile company is able to react to changes more quickly. These companies have continues improvements in order to response rapid to unforeseen events. In detail, they describe agile manufacturing as a production process, which should be able to produce new products quickly with machines that can be easily reconfigured.
This early description of the concept was well received by researchers and further definitions of the term agility and agility manufacturing are based on that investigation.[47]

Kidd express this concept similar and points out that agile manufacturing has to use highly developed technologies and well knowledgeable employees in order to create customized products.[48]

Also, Goldman et al. compare agile manufacturing with a system, which is capable to operate profitable while continually reacting to unforeseen changing customer desires. The following four principles for agility are formulated by him:[49]

- Delivering value to the customer
- Being ready for change

[47] c.f. Yusuf *et al.* 1999, p. 34

[48] c.f. Kidd 1995, p. 3

[49] Rimienė 2011, p. 894

- Valuing human knowledge and skills and
- Forming virtual partnerships

Yusuf et al. summarize the main definitions and comprehend them by defining agility as “the successful exploration of competitive bases (speed, flexibility, innovation proactivity, quality and profitability) through the integration of reconfigurable resources and best practices in a knowledge-rich environment to provide customer-driven products and services in a fast changing market environmental.”[50]

They point out four main concepts, which are interactively working together in order to reach a high agility in manufacturing (Figure 12): [51]

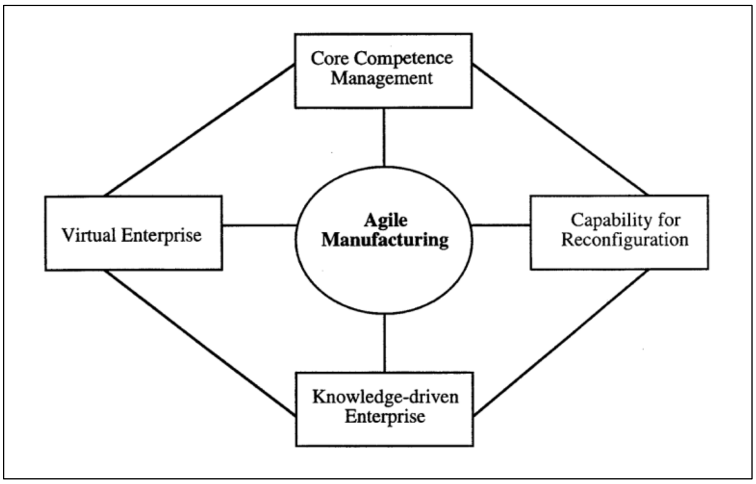

Figure 12: The Core Concepts of Agility[52]

- Core competence management describes the basic expertise, knowledge and skills, which a company or individual person has.

- Virtual enterprise is an alliance of companies in order to work together for a defined time period. This should improve both companies’ competencies and resources.

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[50] Yusuf *et al.* 1999, p. 37

[51] c.f. Yusuf *et al.* 1999, pp. 37–40

[52] Yusuf *et al.* 1999, p. 38

- The capability for re-configuration helps a company to realign their business more easily to external changes and opportunities. It has the advantage to be faster at the market with new products or processes.

- A knowledge-driven enterprise uses the experience of people, lessons-learned workshops and other know how. Agile companies have the desire to gain knowledge from processes and to share it with the work force.

Schurig et al. develop this concept further and focus on different aspects of agile manufacturing. First, companies have to be prepared proactive for uncertainties in order to react fast and accurate to changes. Therefore, the management have to continuously investigate the environment and contemplate suitable measures along the whole value chain.
To be profitably at any time is furthermore a crucial characteristic. This guarantee that in an upward trend the company can make higher profits whereas in a downward movement no losses are being incurred.[53]

Sharafi states that change processes can mainly spit up into external (e.g. changing of customer requirements, law changes, etc.) and internal (improvement of production process, modularisation efforts, etc.) factors.[54] Furthermore, changes takes often place within a complex product development process in the engineering area and contains product changes by form, material, quantity, dimensions etc.[55]
Furthermore, Nyhuis explains that for changes within production system, demand fluctuations and design changes are the most occurred ones.[56]

2.4.2 Further Terms

Especially in the German spoken countries the term flexibility and transformability are widely used within production systems. To include these terms into the agility consideration it is necessary to distinguish between the definitions.

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[53] c.f. Schurig *et al.* 2014, p. 957

[54] c.f. Sharafi 2013, pp. 2–3

[55] c.f. Sharafi 2013, pp. 36–37

[56] c.f. Nyhuis 2008, p. 14

Flexibility describes the ability to react fast and with minimal financial expenditure to influencing factors. The area in which production systems have to be flexible is defined in advance.[57]
As defined by Chryssolouris three objectives of flexibility are available, which Wiendahl et al. further extended to all kind of changeability classes, agility included:[58]

- Product flexibility, which allows to produce variants of parts with the same machines
- Operation flexibility, which allows to produce with different machines and several operations a set of products
- Capacity flexibility, which allows a manufacturing system to shift between operating points easily to react to demand changes.

Transformability extends flexibility due to the possibility to shift the predefined corridors to a new area. Herewith, organisational and engineering changes can be undertaken reactively and occasionally even proactive.[59]
In Figure 13 the difference of flexibility and transformability is illustrated.

ElMaraghy and Wiendahl use the term changeability to classify flexibility, transformability and agility with respect to production and product levels. They try to compare these three different terms and compare them.[60] Based on their work six classes for production and product levels are described.

While agility influence both highest levels, which is the production network and product portfolio, transformability is allocated at the second highest level, the factory and product group. Flexibility affects all underlying levels, for production from the segment down to the station, for products from the product instance down to the individual part elements (Figure 14).[61]

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[57] c.f. Abele *et al.* 2006, p. 433; c.f. Sethi and Sethi 1990, p. 295

[58] c.f. Wiendahl *et al.* 2007, p. 786

[59] c.f. Nyhuis 2008, pp. 24–25

[60] c.f. Wiendahl *et al.* 2007, p. 786; c.f. ElMaraghy 2008, pp. 11–13

[61] c.f. ElMaraghy 2008, pp. 11–13

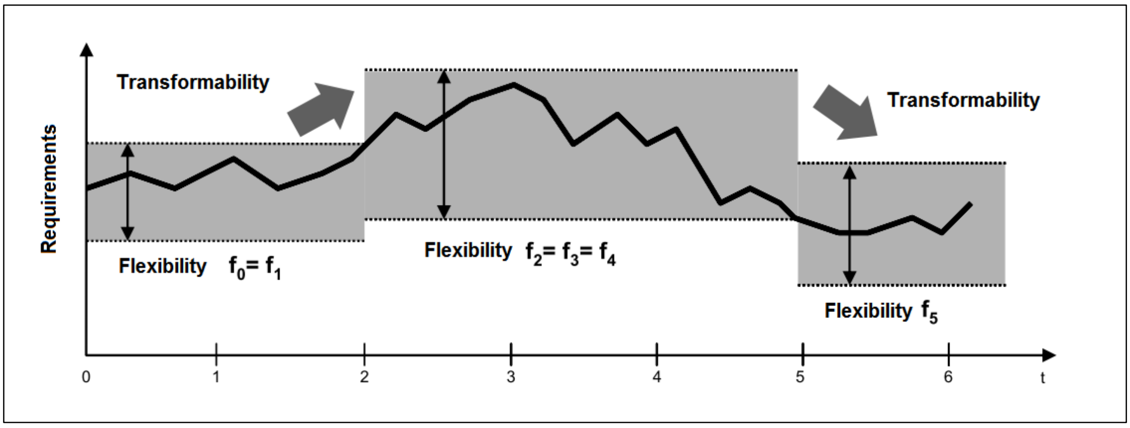

Figure 13: Difference of Flexibility and Transformability. Own Representation based on Zäh 2005[62]

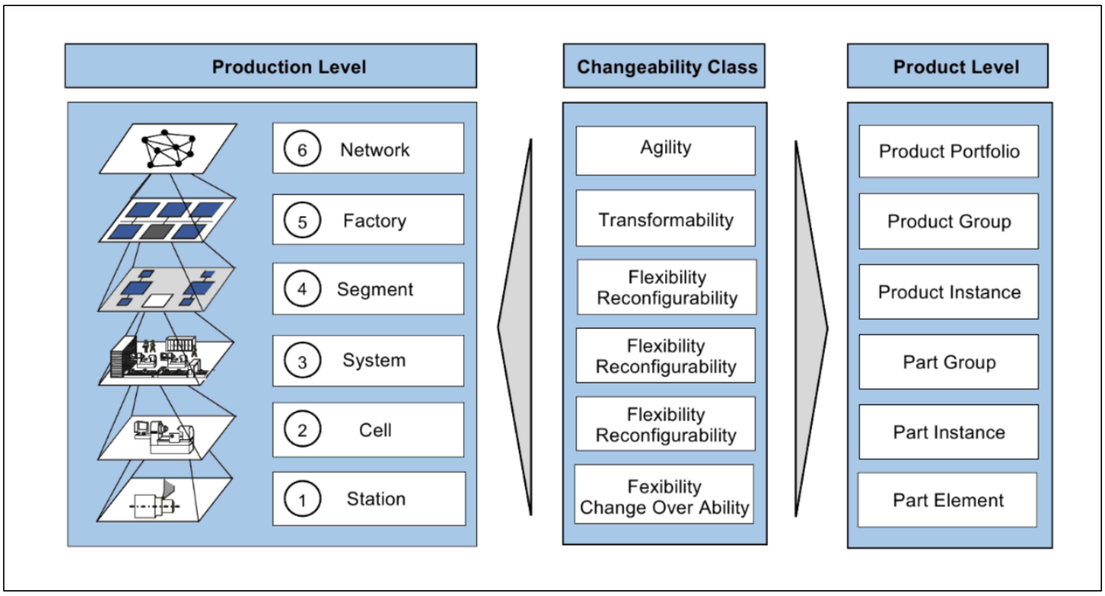

Figure 14: Corresponding Hierarchies of Production, Changeability and Product Levels[63]

2.4.3 Lean in Cooperation with Agility

The first lean production concepts was described by the authors of the 'Toyota Production System' and further developed by authors of 'The machine that changed the world'.[64]

[62] c.f. Nyhuis 2008, p. 25

[63] ElMaraghy 2008, p. 11

[64] c.f. Drew *et al.* 2004, pp. 4–6

The basic concepts of lean is to eliminate waste from any kind of system and process. Famous concepts which are developed from this basic approach are e.g. KAIZEN, Just in Time (JIT), Total Quality Management (TQM) and Kanban.[65]

Several researchers try to distinguish and further to combine the agile and lean approach.
Dove declares that lean management is significant for being agile within a company. He states that leanness is focused to increase the productivity at operational level whereas the goal of agility is to prepare a company strategically to unforeseen events. He further mentioned that the requirements for agility and leanness have the same background, as agile is an advancement of lean (Figure 15).[66]

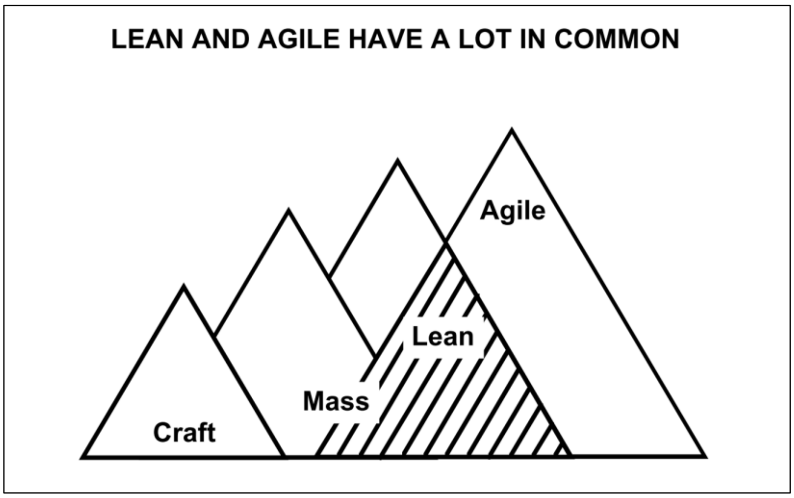

Figure 15: Overlapping Of Lean and Agile[67]

Similarly, Naylor et al. describe the goal of agile manufacturing as to be able to reconfigure its process as fast as possible with constrain to eliminate waste. On the other hand, lean has the major aim to eliminate non-value adding activities, or muda, without giving attention to flexibility. They

[65] c.f. Dove 1996, p. 10

[66] c.f. Dove 1996, p. 10

[67] Dove 1996, p. 10

introduced the term ‘Leagility’ in order to describe the integration of lean and agility.[68]

Furthermore, the German researchers Fisser et al. describe that reducing a firm’s resources so that it is still possible to be transformable and flexible is the common ground to install both approaches. They eliminate each other disadvantages but the crucial point is to find the similarities of both approaches.[69]

2.5 General Considerations of the Principles

For this thesis it is investigated how product design influences the development process and the production stage in general. Therefore, the traditional product development process is being used. The simple classification into product design and production preparation of Eigner and Stelzer is further used in this thesis.
Nevertheless, the investigation can be allocated to any PDP, as every derived process includes a stage in which the product is designed and the production is initialized.

Furthermore, the product architecture modular and integral design is considered within the different product design concepts. As platforms are based on modules this concept is considered within the modularisation view.
Also, standardization is a general concept to simplify parts and processes and will be considered within the individual product design concepts, which will be described in the next chapter.

For agile manufacturing the basic definition from Schurig et al. is used to evaluate the product design concepts. As agility has one focus to prepare the company proactive for uncertainties, product design offers the ability through suitable product architecture, platform thinking or specific design concepts to provide the possibility to fulfill easily and fast changes to the designed products in any stage of the product development process.

[68] c.f. Naylor *et al.* 1999, p. 108

[69] c.f. Fisser *et al.* 2006, p. 387

The changes are narrowed to the external view, as agility aims at unforeseen changes. Furthermore, as product design is part of development process and Nyhuis and Sharafi declare that engineering changes within a PDP are in general design changes and demand fluctuations, the thesis will focus on these two areas.[70] Design changes will be further split up into two influence areas and will be explained in Chapter 5.1.

[70] c.f. Nyhuis 2008, p. 14; c.f. Sharafi 2013, pp. 36–37

3 Product Development Process Concepts to Influence Agile Manufacturing

Product design is only part of a product development process, however the goal is to evaluate the impact of design concepts on the agility within the development and the production stage. Therefore, it is worthwhile to outline some of the main approaches, which are occurring during the whole product development process.

The literature search is narrowed to concepts, which are not only considered within the product design stage. Nevertheless, the concepts should have a focus on agile manufacturing. The investigated and considered concepts are Delayed Product Differentiation, Set Based Design, Simultaneous Engineering and Front-Loading. These concepts will be explained in detail in this chapter.

Several product design concepts, which will be described in Chapter 4, are also part of different product development process concepts. Standardization, modularity as well as some of the Design for X approaches are often included in the concepts.

3.1 Delayed Product Differentiation

Delayed Product Differentiation (DPD) describes the possibility to create product variants late in the product development phase.
On the one hand, the final product shape can be delayed due to the use of modules and standard components instead of using an integral design (Figure 16), on the other hand the manufacturing process can be restructured. [71]
Both approaches give the advantage to avoid redesigning the product if the customer wish or the market changes late in development process, which allows more flexibility within a specific range.

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[71] c.f. He *et al.* 1998, p. 105; c.f. Lee and Tang 1997, p. 40

Although two main approaches of delayed product differentiation are standardization and modularization, the DPD is still a worthwhile approach to consider in detail.

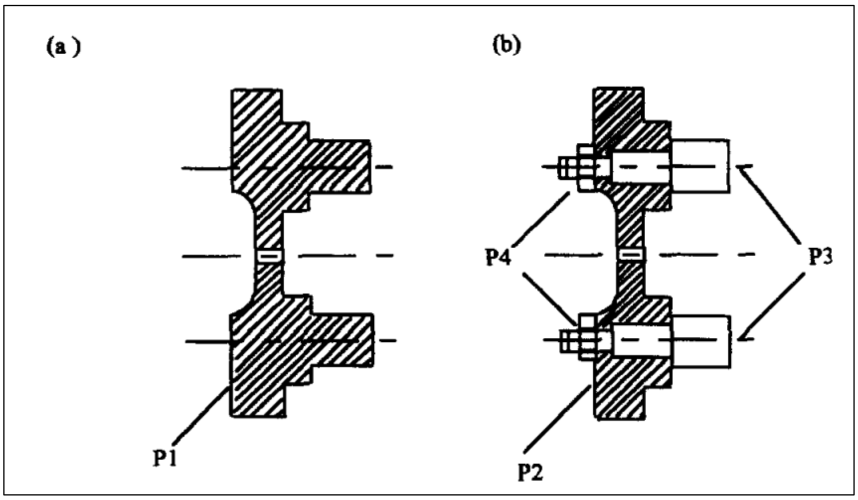

Figure 16: Two Types (a) Integral design, (b) Differential design[72]

Lee and Tang illustrate with a model the benefits and limitations of the three basic concepts of DPD, standardization, modular design and process restructuring.[73]

Standardization is only effective if the part can be used along the whole product portfolio and if the investment cost and incremental processing costs are low. The advantages of standardization can be seen in Figure 17. Instead of doing each operation separately the merging of operation allows to delay the differentiation to a later point.

[72] He *et al.* 1998, p. 105

[73] c.f. Lee and Tang 1997, p. 49

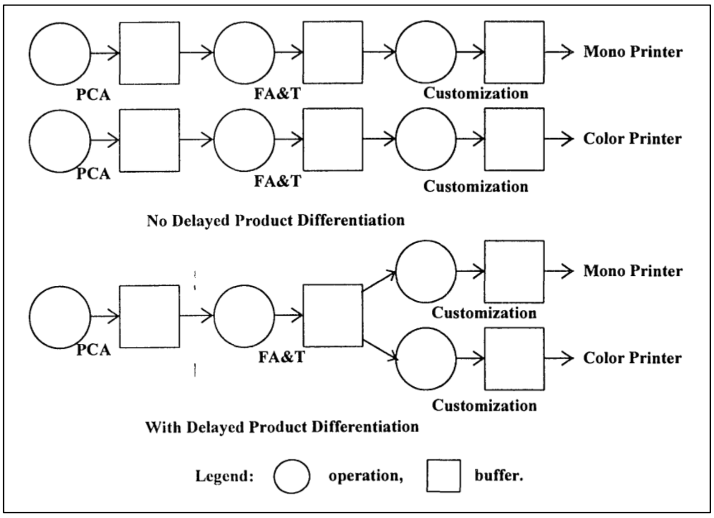

Figure 17: Standardization of Parts[74]

Using modular design for delaying the differentiation means to split one integral part into two modules with one common part and one new part, which can defer the decision. This is preferred if inventory cost, incremental lead time and incremental processing costs are low.

In Figure 18 the advantage of splitting the frame of a dishwasher is illustrated.

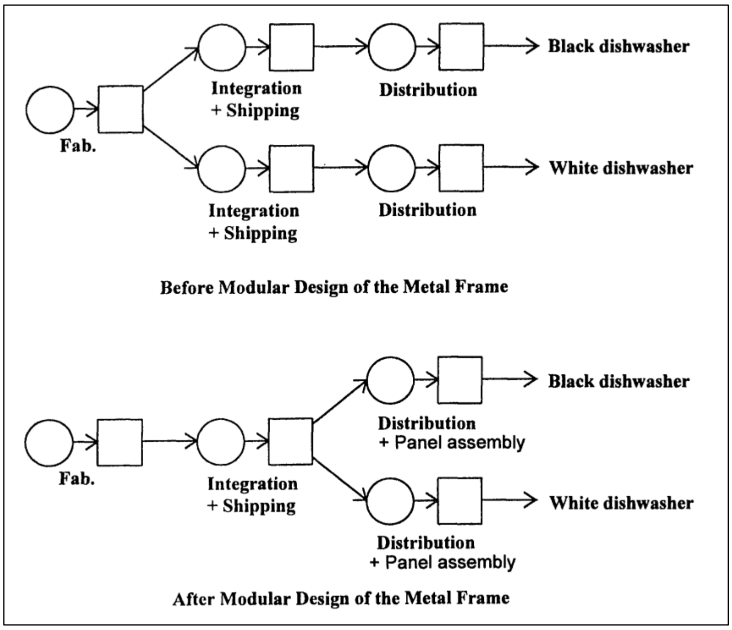

Figure 18: Modular Design of Parts[75]

[74] Lee and Tang 1997, p. 45

[75] Lee and Tang 1997, p. 46

The integration and shipping can be done for both versions together and the final distinction is done at final distributor or customer. Another famous example is the power supply from Hewlett-Packard printers. Due to the modularisation of the plug and putting several country specific plugs into the equipment of the product, the final assembly can be done by the customer.[76]

The last approach to delay the differentiation of a product is within the production process itself. A manufacturing operation can be divided into one common step for all products and one step for the variants, which allows a delay. This approach has advantages if the common step has a low lead time and the individual step is a high value-added operation.
One way to achieve late process differentiation is to split up an operation into sub processes and to operate the common process first (Figure 19).
Another possibility is to reverse the sequence in order to operate the common process first and together (Figure 20).

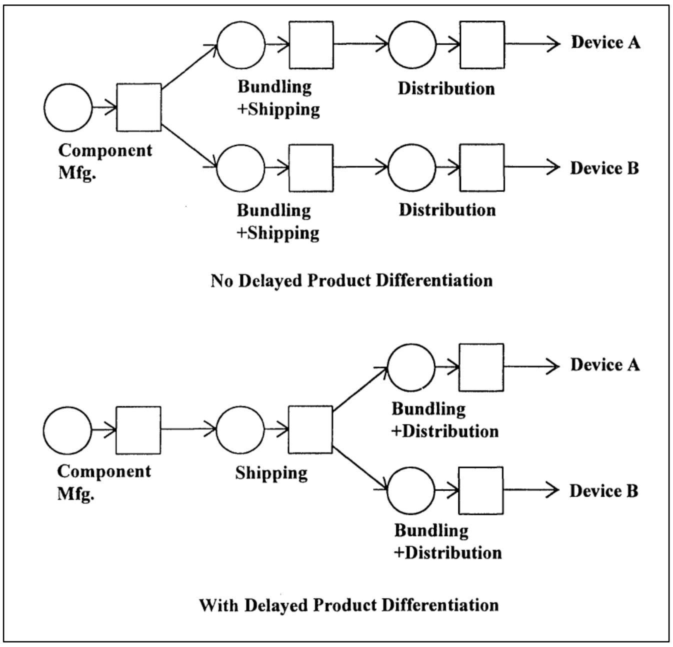

Figure 19: Process Restructuring: Postponement of Operation[77]

[76] c.f. Brun and Zorzini 2009, p. 206

[77] Lee and Tang 1997, p. 47

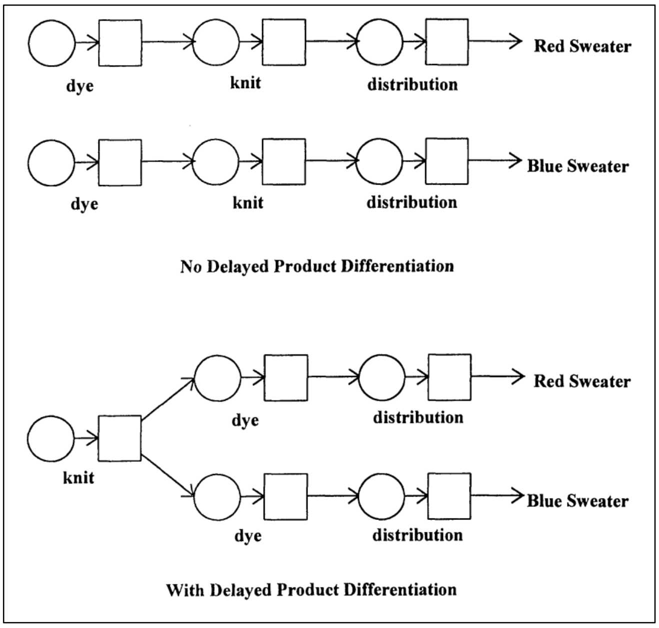

Figure 20: Process Restructuring: Reversal of Operations[78]

3.2 Set Based Design

Set Based Design or Set Based Concurrent Engineering is an approach to define the final design of a product at the latest moment and develop concurrently several design concepts.[79]

The opposite of Set Based Design is Point Based Design, which focuses on just one solution at the beginning of the design stage.

The procedure of Set Based Design in illustrated on an example of three specialities, who are working in separate areas and trying to find a common solution (Figure 21). At first, each designer has its own area within the design space. They develop separate solution, which may not overlap (1). With the next step each group enlarge their design area in order to generate a small overlap between their solutions (2). After finding some commonality, they work together to focus and enlarge their option in order to generate a solution, which satisfy all necessary requirements (3). Then, each group reduce their own solution area to a smaller region (4) until only one solution is remaining (5).[80]

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[78] Lee and Tang 1997, p. 49

[79] c.f. Smith 2007, pp. 111–112

[80] c.f. Bernstein 1998, p. 49; c.f. Raudberget 2012, p. 19

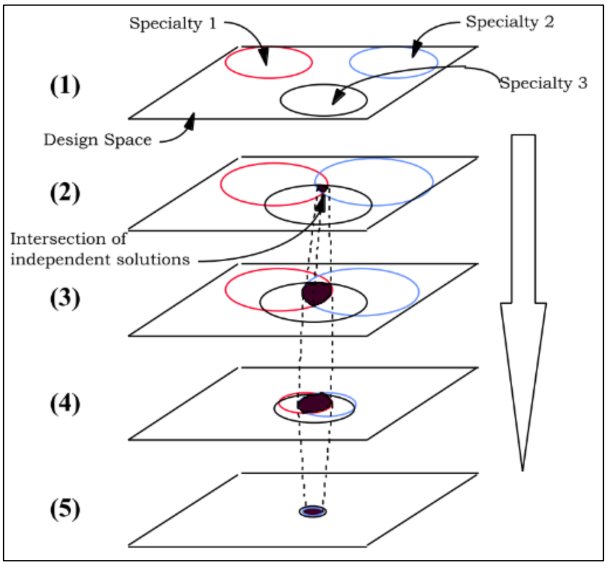

Figure 21 Set-Based Design Process[81]

Set Based Design has parallelism with the method of controlled convergence (Figure 23) and the design-build-test cycle (Figure 22). Bernstein describes that all three methods offer multiple design alternatives, nevertheless only Set Based Design allows speciality groups to work in the beginning independently within their design area.

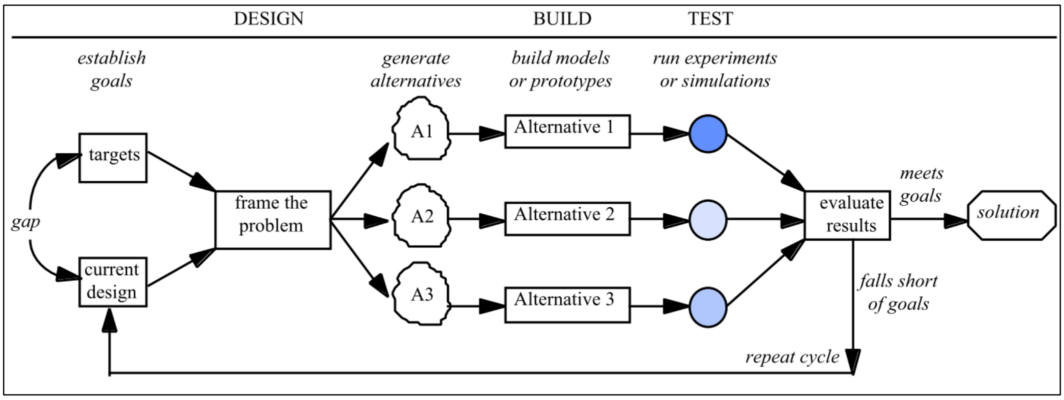

Figure 22: The Design-Build-Test Cycle[82]

[81] Bernstein 1998, p. 49

[82] Bernstein 1998, p. 59

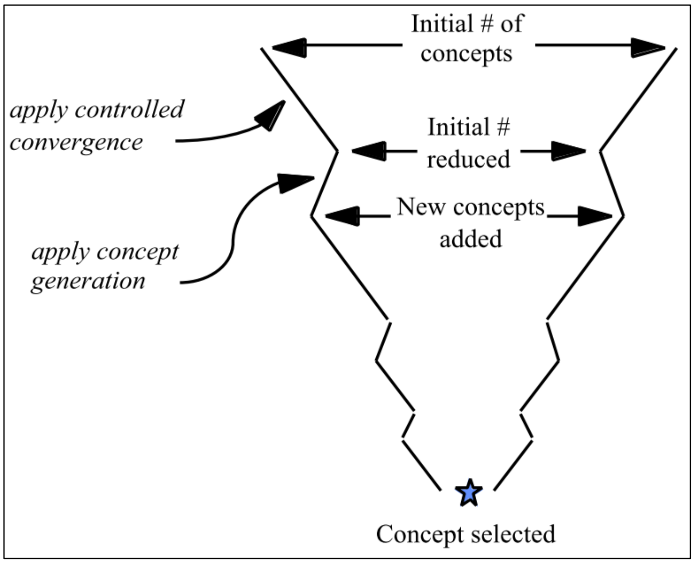

Figure 23: Method of Controlled Convergence[83]

The aim of Set Based Design is delaying the final design decision to the latest possible time while still developing the product. This results to a shift of the cost determination after the design stage (Figure 24). Therefore, stakeholders can still influence the development of the product with less changing costs.[84]

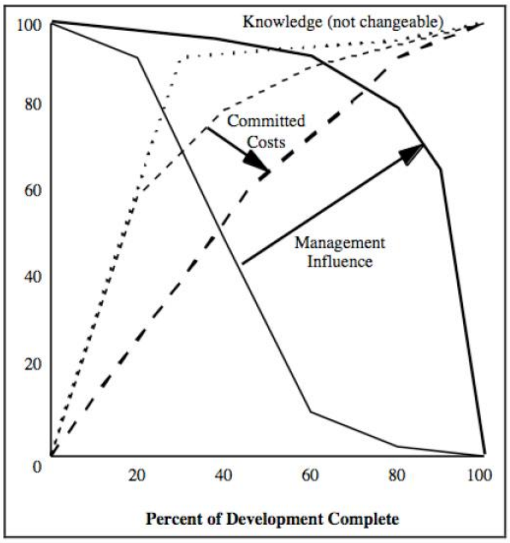

Figure 24: The Effects of Set Based Design[85]

[83] Bernstein 1998, p. 58

[84] c.f. Singer *et al.*, p. 38

[85] Bernstein 1998, p. 46

Nevertheless, Smith points out that the applicability of Set Based Design is limited. The nature of human is to make early decisions than keeping opportunities. He describes on the example Toyota, which is an applicant of Set Based Design that the whole company culture has to be oriented for delaying the decision.[86]

3.3 Simultaneous Engineering

Simultaneous Engineering or Concurrent Engineering is an approach within the product development process, which aims to overlap the accomplishment of processes or tasks.[87] The opposite is traditional design development, which handles the stages sequentially. A comparison of these two approaches can be seen in Figure 25.

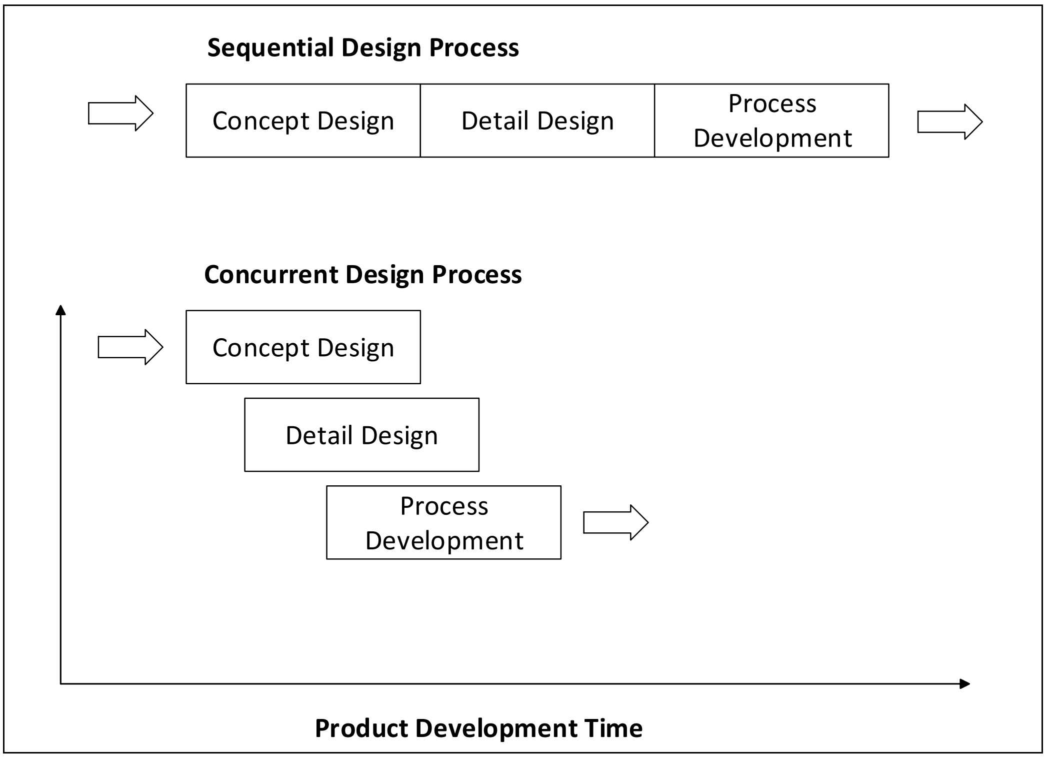

Figure 25: Comparison Sequential and Concurrent Design Process. Own Representation based on Salomone 1995[88]

[86] c.f. Smith 2007, pp. 122–124

[87] c.f. Ehrlenspiel and Meerkamm 2013, p. 218; c.f. Salomone 1995, p. 1

[88] Salomone 1995, p. 16

Traditional design development has mainly be used until the 1980's before three main reasons have caused to changes in the development procedure:[89]

- At first, the increased pace of technology required a faster response to new technologies and put pressure on design teams. They had to reduce the time to market in order to provide customers the latest technology and to have an advantage to competitors.

- Secondly, due to the pressure of developing products faster manufacturing inputs were ignored, furthermore the marketing could not integrate the need of the customers. The results of missing targets in the marketplace and non-producible products lead to the output that just reducing the development time is not the answer.

- Lastly, several computer-aided tools, like computer-aided design (CAD) or computer-aided engineering (CAE) helped the designers to analyze and see their products in a more easy way. Furthermore, methodologies like the previous explained Design for Manufacturing and Assembly guidelines as well as better marketing tools, like quality function development (QFD) helped to combine different areas into the development process.

Chris Baylis, general manager at the Nissan European Technology Centre, mentions several possible positive effects of Simultaneous Engineering:[90]

- Shorter development time
- More efficient product development (less costs due to right developing at the first time)
- Higher product quality
- Less unconsidered topics during the development

[89] c.f. Salomone 1995, pp. 1–4

[90] c.f. Baylis 1994, p. 20

3.4 Front-Loading

Thomke and Fujimoto describe Front-Loading as a product development process, which seeks to improve development performance by shifting the identification and solving of design problems to earlier phases of a product development process.[91]

The two main approaches, which are included in Front-Loading, are Project-To-Project Knowledge Transfer and Rapid Problem Solving.[92]
Project-To-Project Knowledge Transfer ensures that problems, which occurred and solved at earlier projects are discussed at the beginning of a new project. Lessons-Learned workshops guarantee that the same problems are not disrupt the project progress again. These workshops should also fulfill the documentation at the end of each project and summarize occurred main issues.
Rapid Problem Solving includes all tools, which help the designer to determine the product more precise at an early project stage. Virtual engineering (Digital Mock Ups, DMU), Rapid Prototyping (3D Printing) or Simulations (Finite Element Methods, FEM) are some of the most used tools nowadays.

3.5 Conclusion of Product Development Process Concepts

The above described concepts Delayed Product Differentiation, Set Based Design, Simultaneous Engineering and Front-Loading will be covered within the thesis. Their usage is within the whole development process, nevertheless they have a big impact during the product design stage.

The next step is to accomplish a literature research on main product design approaches, which are just occur within the product design stage. This concepts will be defined in Chapter 4.

[91] Thomke and Fujimoto T. 2000, p. 132

[92] c.f. Thomke and Fujimoto T. 2000, p. 132

4 Product Design Concepts to Influence Agile Manufacturing

As described in Chapter 2, product design is part of the product development process and is a stage where the product is physically be designed. It includes turning the vision of a product into feasible technical solution, concept development and the styling of a product.[93]
The investigated product design concepts should have their influence only in the stage product design. Concepts, which will be used within the whole product development process are described in Chapter 3.

As product design is a complex process, it is reasonable to classify different types of product design.
After the classification the design concept, “Design for X”, which is a collection of main design methods within the product design stage, will be introduced. This umbrella term as well as some of the most important derived concepts are described. These concepts have been collected by several research papers, which are already focusing on agility and possible levers to influence it.

The last subchapter part contains a summery of previous detailed investigation on product design and their influence on agility. Furthermore, design for agility concepts, which mainly affects the production preparation and manufacturing stage, are described. They suggests, how the production steps should be arranged to influence the agile manufacturing.

4.1 Types of Product Design

There are several ways to classify design. One way to distinguish product design is the categorisation into the development effort. Otto and Wood distinguish between original, adaptive and variant design:[94]

[93] c.f. Otto and Wood 2001, pp. 5–7

[94] c.f. Otto and Wood 2001, pp. 7–9

- Original design describes designing of products, which have a novelty status. This means that the design results into an invention. These products are very development intensive and the risk of success is relative low. Nevertheless, these products have the opportunity to develop and enter a completely new markets.
- Adaptive design seizes the basic ideas of existing concepts and a new product will be developed to the changed needs or to refine an invention. The shape of these designs can be taken very novel, nevertheless the effort for designing is reduced as the basic concept is already developed and used.
- Variant design is modifying the parameters (geometric size, material, etc.) of an existing product in order to create new product varieties. The basic configuration stays the same in order to minimize the development effort. This design concept is implemented for scaled product variants.

Another classification of design process can be done related to the field or area, where the designing stage takes place.
Several disciplines have to be combined in order to create a whole product. For a complex products different areas, e.g. mechanical engineering, electrical engineering, industrial design, architectural design, material design, aerospace design, etc., are include. The entire design team and work is depended therefore on the scope of the product and on the field of the industry.[95]

For this thesis original, adaptive and variant design strategies are considered, nevertheless the area of products is narrowed to the mechanical engineering field.

4.2 Product Design Methods

In order to design a product properly several methods are available to support the design engineer. The umbrella term "Design for X", which covers all design methods within the product design process, is explained in detail as well as some of the main derived approaches.

[95] c.f. Otto and Wood 2001, pp. 9–11

As the main and important general design principles for demand fluctuations are described in the DFA and DFM concepts, these qualitative guidelines will be considered in detail. Bauer mentions that most of the available qualitative DFX guidelines are described within these two approaches.[96]
Furthermore, as DFA and DFM are already established since 1970, they also tackle other goals like improving quality and reducing the time to market, which shows the main importance of the DFA and DFM approaches.[97]

Furthermore, the previous definition of agility means to react fast to changes and as design changes are included in the thesis (See Chapter 2.4.1), the 'Design for Variety' approach will be considered, because it supports to derive new variants in a more sufficient way.

Lastly, the ability to switch between different materials is crucial in an agile environment. Although, this approach is developed in the recent years, it contains main approaches to react faster to unforeseen changes. Therefore, the Design for Switchability concept will be included in this work.

The last part contains a comparison of design concepts and their limitations within the product design.

4.2.1 Design for X

'Design for X' (DFX) is a common term to describe and group design guidelines to achieve a specific goal. The 'X' stands either for stages in the product lifecycle or for a specific virtue.[98]
Product lifecycle design concepts are for example Design for Manufacturing, Design for Assembly, Design for Service or Design for Recycling.
Examples for virtue design guidelines are Design for Quality, Design for Variety, Design for Environment, or Design for User-friendliness.

The term DFX has been established after researchers have described various design concepts. The first design concept, 'Design for Assembly' (DFA) was described by Boothroyd and Dewhurst. The goal was to include

[96] c.f. Bauer 2007, p. 13

[97] c.f. Kuo *et al.* 2001, p. 242

[98] Dombrowski *et al.* 2014, p. 385

the production process already early in the design process to guarantee the ease of assembling of products. Based on that idea Boothroyd and Dewhurst further developed the ‘Design for Manufacturing’ (DFM) concept. Their goal was to design a product, which is easy to fabricate and therefore avoid mistakes during the production stage and redesigning of the product.[99]

Bauer states that the different DFX approaches can be classified in several ways. He lists more than 40 Design for X Guidelines, with the outlook that there are even more approaches.[100]

The guidelines, which are included in the various Design for X approaches are not uniform. Researchers are clustering the guidelines differently according to the DFX versions, furthermore many of the guidelines can be allocated to more than one category.[101]
The guidelines should be qualitative and universal applicable but specific enough to use. The visually illustration with pictures should help to understand and apply the rules.[102]

4.2.2 Design for Assembly and Manufacturing

Design for Assembly is an approach to simplify assembling steps and to support the manufacturing while assembling the products.
Design for Manufacturing is an approach to make piece parts easier to produce.
Although Design for Assembly and Design for Manufacturing are individual Design for X approaches, researcher nowadays sum them up to the approach: Design for Assembly and Manufacturing.
As mentioned above, Boothroyd and Dewhurst did the pioneer work of Design for Assembly and Manufacturing in 1970. The two researchers give suggestions how to design parts and assemblies for the ease of production. Nevertheless, their recommendation catalogue is very detailed and they give

[99] c.f. Boothroyd *et al.* 2011, pp. 1–26

[100] c.f. Bauer 2003, p. 3

[101] c.f. Kuo *et al.* 2001, p. 242

[102] c.f. Bauer 2007, pp. 13–14

advice for each manufacturing process, like machining, casting, forging, etc.[103]
Based on that detailed description other scientists further developed the DFA and DFM approach and try to summarize and group these guidelines to qualitative guidelines.

4.2.3 Design for Variety

Martin and Ishii have founded the term Design for Variety (DFV) in 1996. They develop methodologies to simplify the complexity of developing new variants in order to reduce the costs of the several product variants.
With the help of indices which help to evaluate the cost and effectiveness of product variety, a product should be divided into common parts and parts which are changing for each variant.
Furthermore, they develop indices for products, which will be changing over time. This should help to categorise parts according to the likeness of changes over time.[104]
Siddique *et al.* point out that Martin and Ishii DFV approach refers to "product and process design that meets the best balance of design modularity, component standardization, late point differentiation and product offering" and support this approach.[105]

Based on that research of Martin and Ishii, Kipp and Krause derive and describe specific guidelines in order to visualise the complexity of product variant design. They also include the architecture of a product in their guidelines as the structure is a crucial leverage for the effectiveness of a later variant design.[106]

4.2.4 Design to Switchability

Design to Switchability (DFS) or Material Switchability is an approach to use a different material if the raw material price of the preferred one is increasing strongly. The background has been investigated by the consultant company McKinsey. They found out that volatility in raw material prices has increased

[103] c.f. Boothroyd *et al.* 2011, pp. 1–26

[104] c.f. Martin and Ishii 2000, pp. 1–3

[105] Siddique *et al.* 1998, p. 3

[106] c.f. Krause and Kipp 2008, pp. 428–431

strongly in the last years. Furthermore, they defined Material Switchability as a possibility to increase agile operations in the manufacturing especially within the product development stage.[107]

Although their survey mostly covers materials within the food, beverage manufacturing industry and steel industry it gives a good overview about how important changes of material raw prices are for agile operations.

Due to the newness of this approach there are no qualitative guidelines available. Because of that, this approach is covered in total and is not split up into individual guidelines.

4.2.5 Limitations and Interference of the DFX Guidelines

Lindemann discusses conclusions about the general definition of DFX guidelines of Ulrich and Eppinger as well as from Otto and Wood. He points out that those researcher not clearly state when a specific Design for X approach and the derived guidelines is useful or not by using the dependency of the specific situation. These researchers only mention that other factors like development time or cost have to be considered if a specific DFX approach is used. Therefore, Lindemann recommends using dependency matrices to address this problem further in detail by comparing different requirements and the interaction with each other in order to get a better overview.[108]

Although these matrices would help to illustrate several overall domains, a detailed investigation of the DFX approaches of Lindemann is missing.

Also, Bauer mentions that the different DFX guidelines can support, interfere or have no effect on each other. He suggests comparing all necessary guidelines with each other by a relation matrix. In cases of contra-productive and conflictive guidelines a prioritization should focus on the more important requirements.[109]

Dombrowski et al. sum up guidelines of different Design for X approaches and formulated qualitative design guidelines, which serves recommendation and not as rules. They explicit mention the limitations of that comparison by

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[107] c.f. Manyika *et al.* 2012, pp. 10–11

[108] c.f. Lindemann 2007, p. 3

[109] c.f. Bauer 2003, pp. 4–5

not explicit include companies specific situations. Furthermore, the guidelines can hinder or support each other and have to be analyzed by a cross impact matrix.[110]

4.3 Pre-Investigation about the Influence of Product Design on Agility

Several researchers already investigate the interface between specific product design approaches or product architecture on the agility of companies or particularly on agile manufacturing.

Kässi *et al.* seize on the idea to divide modularity in several ways and to create a matrix, which should help to distinguish the level of product modularization. The authors investigate the effect of modules within a product and how it supports to react faster to market changes. Furthermore, the interaction between modularity and customer involvement are demonstrated and highlighted.[111]
Although, the potential of modularity is shown in one example, the direct link to agility and how it supports agile manufacturing is missing.

Saraji and Izadpanahshahri accomplish a literature review about the role of product architecture in agile manufacturing firms. In their study, they describe different research results regarding the product architecture and agility area and highlight the potential of the product architecture in that field.
They also list the advantage and disadvantages of product architecture especially modular design from several literature sources according to the agility capabilities Proactiveness, Customer focus, Responsiveness, Flexibility, Quickness, Competency and Partnership.[112] This research work is very detailed and shows the possibility of modular design, nevertheless other concepts are not investigated.

Anderson describes in the book “Agile product development for mass customization” different approaches to develop a product in an agile

[110] c.f. Dombrowski *et al.* 2014, p. 389

[111] c.f. Kässi *et al.* 2008, pp. 57–59

[112] c.f. Saraji and Izadpanahshahri 2012, pp. 43–45

environment. He underlines the importance of standardization and rationalization in order to reduce the cost of the internal part and assembly variety. Besides the importance of the right process planning, the future trend of modularisation and the potential of that design is expressed.[113]

Besides the specific investigation between product design and agility, which are described above, several researcher formulate "Design for Agility" rules. These rules mostly affects the production preparation and manufacturing and how the production steps have to be arranged.

Vinodh et al. illustrate an overview of major papers, which are dealing with agile manufacturing. They allocate the work of different researcher into twelve agility directions, which one is called "Design for Agility". Within this area the design term is expanded from the original product design area to process design, manufacturing design and service design.[114]

Lee especially investigates the interference of product architecture and the structure of a manufacturing system.
He suggests that assemblies should be designed so that precedence constraints for subassemblies are arranged in a certain way. The subassemblies, which have the shortest completion time of machining operations, should be done first and those, which have a long operation time, at the end. This should give the advantage of shortening the lead time within the manufacturing.
Furthermore, he formulates a design for manufacturing system rule in order to allow reconfiguration at low cost and with less movement of the machines.[115]
Lee's "Design for Agility" rules mostly consider the agile production process without giving suggestion, which design concept should be used in order to support agility.

Kusiak and He focus on "Design for Agility" rules for improving the scheduling of a manufacturing system. They formulate and test four design rules, which

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[113] c.f. Anderson 1997

[114] c.f. Vinodh *et al.* 2009, p. 579

[115] c.f. Lee 1998, pp. 1025–1031

include the modular design of a manufacturing systems, designing a product with robust scheduling characteristics, streamlining the flow of a product in an assembly line and the reduction of stations within an assembly line.
The advantages of including these rules in the product and manufacturing design are shorter throughput time and lowering the cost within the production.[116] Also, Kusiak is focusing on the process allocation and not on the product design.

The above described design for agility rules covers mainly, how to arrange production steps to improve agile manufacturing. As they have no main focus on the product design, these rules are not further considered in the thesis.

All described investigations focus on special approaches to influence the agility. In this thesis it is tried to extend the results of this pre-investigation with common design concepts, which are described in general in the literature and have an influence on agility or agile manufacturing. Furthermore, these general approaches are evaluated with companies to figure out, which they already implemented and which they consider useful in their industry.

4.4 Conclusion of Product Design Concepts

For this thesis the Design for X approach is considered but is narrowed to the basic concepts.

As mentioned in Chapter 2.5, the affected change areas are design changes and demand fluctuations. Therefore, the main focused DFX approaches are Design for Assembly and Manufacturing, which have a main influence on the production (See Chapter 4.2). Another main DFX approach is Design for Variety, which supports mainly design changes. Design for Switchability, which is new approach and focuses on shifts of raw material prices, will be also considered in this thesis.

[116] c.f. Kusiak and He 1998, p. 426

The qualitative guidelines of DFA, DFM and DFV are summarized and grouped together to a design catalogue (See Chapter 6.1). This is the base for further investigations of the guidelines.

Due to the newness of the approach Design for Switchability, qualitative guidelines are not available. Therefore, this approach cannot be included in the design catalogue, but is covered in total.

5 Agility Drivers

In order to assess the design concepts related to their impact on agile manufacturing, it is helpful to split up the influencing drivers of agility further.
These drivers are the reason, why agility is very important nowadays and come from the considered change areas; design changes and demand fluctuations, which are described in Chapter 2.5. Design changes will be split up into two main affecting agility areas. Furthermore, the magic triangle of project management (Quality, Time and Cost) will be investigated in respect to agility.

5.1 Design Changes

Design changes take place if the shape or architecture of an existing product varies. This happens if the customer wants to modify an existing version or the market required a new variant of a product.[117]

Firstly, design changes can occur during the development phase, thus before the product is produced.[118] This means that the manufacturing team is not involved yet and the design department is forced to change the product within shortest possible time in order not delaying the Start of Production (SOP).
One possible reason is that the customer has a change request and want to extend the requirements of the product late in the development stage. Another reason is, if the developed product does not meet the expectations of the current market before it is even produced or a competitor brings his product faster to the market with not considered features. These reasons lead companies to modify their actual design.[119] The last example is mostly happening if the products have a short life cycle time.
For these kind of changes the driver ‘Late Changes’ is formulated. In Figure 26 the affected time period within the simplified product development process

[117] c.f. Sharafi 2013, pp. 37–38

[118] c.f. Sharafi 2013, pp. 38–40

[119] c.f. Nadia *et al.* 2006, p. 7

is illustrated. Late Changes arise in during the design stage and ends with the start of production.

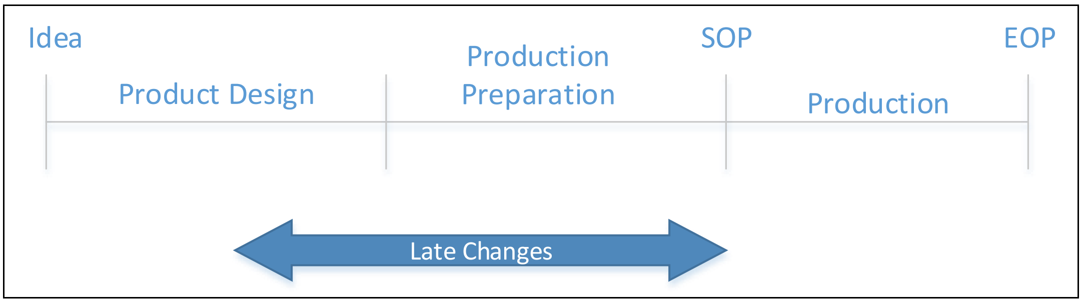

Figure 26: Effected Time Period of Late Changes. Own Representation based on Sharafi 2013[120]

Another design change occurs after the start of production. This has the effect that a new product has to be derived from the existing one, therefore, a new variant of the product is required. This variant can be a new generation version or it is required to modify the product portfolio. [121]

As agility means to react fast to unforeseen events, the generation variants are not considered, because of their continuously evolution. It is more difficult to react to unforeseen changes.

For this case the driver 'Diversity of Variants' is used, which describes the easiness to derive from existing products.

An example, where Diversity of Variants is needed, are products with high complexity and short product life cycle.

In Figure 27 the effected time period of Diversity of Variants is illustrated. As the need of variants takes place after the SOP, the production time period is affected.

[120] c.f. Sharafi 2013, p. 40

[121] c.f. Bongulielmi 2003, p. 12

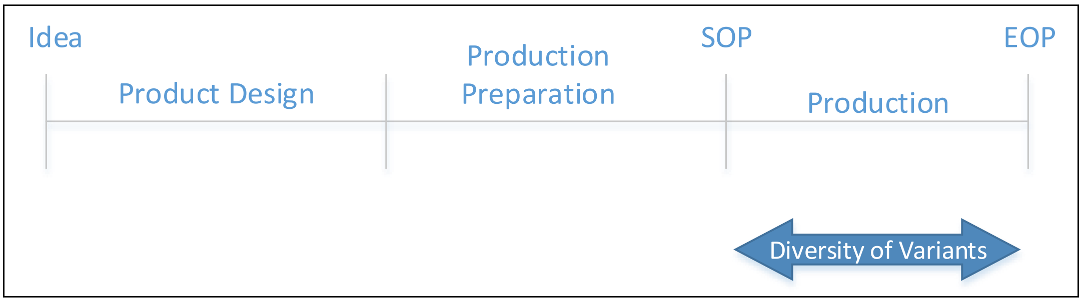

Figure 27: Effected Time Period of Diversity of Variants. Own Representation based on Bongulielmi 2003[122]

5.2 Demand Fluctuations

Demand fluctuations arise every day at the manufacturing industry. The production has to adapt to these changes continuously. Warehouses and further measures are usually present to compensate the fluctuations. If the sales jumps are too high for the regular compensations, the need of agility is present.[123]

The product design stage can help or hinder such volatilities. Therefore, the agility driver 'Quantity' is formulated, to cover and evaluate the influence of product design on the production.

In Figure 28 the effected time period of the driver Quantity is shown. As quantity fluctuations just affect the manufacturing, this driver only occurs during the production period.

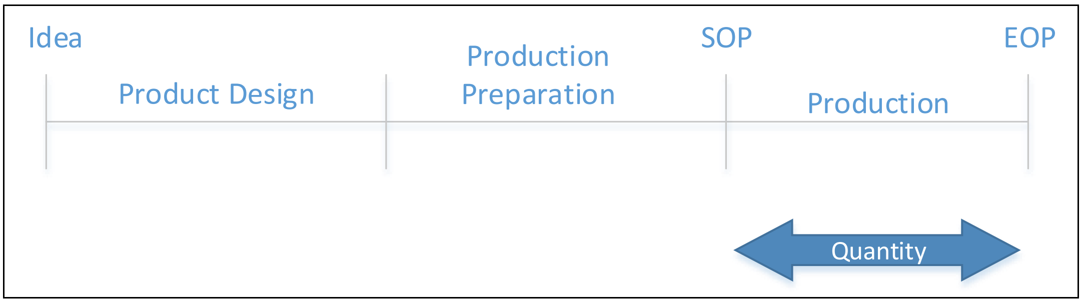

Figure 28: Effected Time Period of Quantity

[122] c.f. Bongulielmi 2003, p. 12

[123] c.f. Schurig *et al.* 2014, p. 957

5.3 Further Drivers and Consideration

In addition to the previous mentioned and defined drivers the magic triangle of project management Quality, Time and Cost is worthwhile to investigate in respect to agility.

The triangle describes the interaction between three important criteria within project management. Time, Cost and Quality are often used to measure if a project is successful or not (Figure 29).[124]

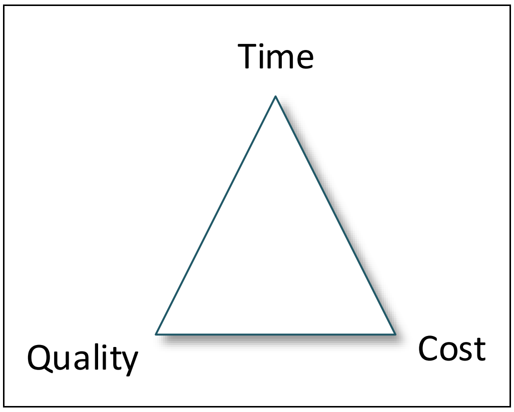

Figure 29: Magic Triangle. Own Representation based on Atkinson 1999[125]

Quality is one of the three parameters. Most of the production companies have included a quality department, which is responsible for the quality of their products.
Nevertheless, Yusuf et al. explains that companies need high quality products in order to remain competitive. Therefore, agile manufacturing has to include all lesson learned from quality management systems like Total Quality Management (TQM), Statistical Process Control (SPC) and Quality Function Deployment (QFD).[126]
Furthermore, to produce high quality products it is required that the design department also considers possible issues very early and adapts the design. Within Design for X, the specific Design to Quality approach supports the engineers with recommendation to avoid common quality issues.

[124] c.f. Atkinson 1999, p. 338

[125] c.f. Atkinson 1999, p. 338

[126] c.f. Yusuf *et al.* 1999, p. 35

Additionally, the previous mentioned Quality function Deployment is a technique to assist Design for Quality.[127]
Also, Devadasan et al. state that nowadays there is a continuous need of high quality.[128] For the need of agility the topic quality has a minor role as sudden quality jumps are not occur.

The next influencing parameter are costs. The cost of a product is crucial for a company's success. In high cost countries, companies are forced to reduce costs in order to stay competitive.[129] Process improvement and restructuring is therefore a common approach to increase the efficiency and keep costs low.
As described in Chapter 1.1 the main costs of a product are mainly determined during the design stage. In general the design approaches like DFX, Standardization, Set Based Design or Delayed Product Differentiation aim at reducing costs. Either, the concepts tackle the manufacturing and assembly costs or they focus on avoiding costs, which occurs by doing the development work again.
As a result, costs are a ubiquitous topic, nevertheless the definition of agility also includes to be profitable at any time (See Chapter 2.4). Therefore, the cost of implementing each concept has to be considered individually. Furthermore, for each guideline of the Design for X concept it has to be investigated, if the implementation cost of this guideline supports later cost reductions.
Raw material costs are considered within the Design to Switchability approach, which allows to switch to a different material if the price of the preferred one is increasing rapidly.

The last parameter of the magic triangle is time. It is nowadays important to bring a product faster than the competitor to the market. Furthermore, customers want nowadays always the latest product and features.[130] This leads to the fact that the product life cycle is decreasing (see Figure 1). Approaches like Simultaneous Engineering focus on that and try to overlap

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[127] c.f. Kuo *et al.* 2001, p. 251

[128] c.f. Devadasan *et al.* 2005, p. 578

[129] c.f. Spence 1984, p. 101

[130] c.f. Lindemann *et al.* 2006, p. 7

the subsequently development processes in order to shorten the development time (Chapter 3.3).
The essential of reacting fast in an agile company eventuate to a decreased developing time, if changes are needed. The term ‘Time to Market’ describes the ability to bring a product faster to the market if the development have already started and external factors force the company to reduce the time to market. The influence area of Time to Market is started from the beginning of the product development process and ends with the SOP (Figure 30).

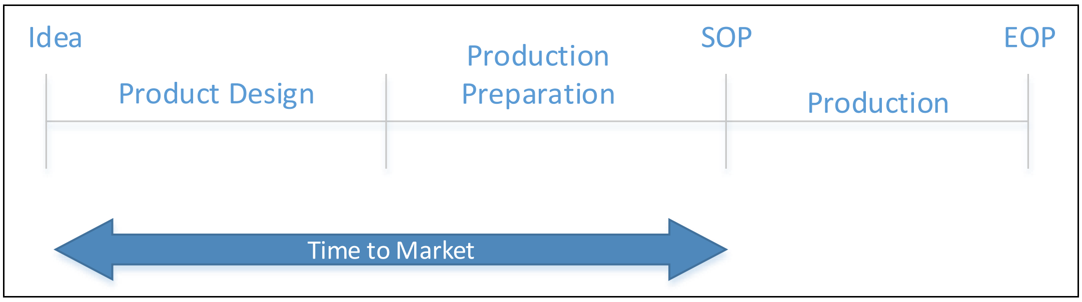


Figure 30: Effected Time Period of Time to Market. Own Representation based on Bischoff 2007[131]

[131] c.f. Bischoff 2007, p. 5

6 Design Recommendation Catalogue

In order to assess the different product design concepts related to the agility levers, it is helpful to create a catalogue, which lists main guidelines. After the formulation, the design catalogue will be evaluated by researcher of several institutes. Based on the evaluation, a design recommendation catalogue will be formulated, which lists the main levers to influence the different agility drivers.

6.1 Design Catalogue

The idea using a catalogue is seized up by researches from the University of Brunswick – Institute of Technology. They have created a catalogue with 96 main Design for X guidelines and allocated the individual guidelines to 12 DFX approaches.[132]

6.1.1 Focus and Formulation of the Catalogue

For the investigation of this thesis, all individual guidelines of the Design for X approach cannot be considered, the main guidelines are listed and allocated to the important design concepts.

As discussed in Chapter 4.4 the considered Design for X approaches are Design for Manufacturing, Design for Assembly and Design for Variety. The described guidelines of these three design concepts within the literature are collected and summarized.

For Design of Assembly, the work of Kuo et al.[133], Anderson[134], Otto and Wood[135], Dowlatshahi[136], Marshall[137], Huang[138], Andreasen *et al*.[139] and Corbett et al.[140] are used.

[132] c.f. Dombrowski *et al.* 2014, p. 385

[133] Kuo *et al.* 2001, p. 245

[134] Anderson 1997, pp. 234–239

[135] Otto and Wood 2001, pp. 663–716

[136] Dowlatshahi 1996, p. 193

For Design for Manufacturing, the guidelines of Kuo et al.[141], Anderson[142] [143], Marshall[144], and Corbett et al.[145] are considered.
For Design for Variety, the research work of Krause and Kipp[146] and Siddique et al.[147] are used.

At first, all guidelines, which are mentioned in the 11 literature sources, are gathered together. As a result, 89 guidelines are listed and allocated to the specific Design for X approach.

The next step is to combine similar guidelines, which are described in the same way or just a little bit different, nevertheless have the same meaning or purpose. Some descriptions of the guidelines are modified at the same time to get a better understanding. Furthermore, examples should ensure the understandable of the guidelines.
Therefore, the list shortens to an amount of 60 qualitative guidelines, which are further considered.

6.1.2 Design Categories

After that narrowing, it becomes apparent that many guidelines aims at similar goals. Although the researcher of the University of Brunswick – Institute of Technology just used a collection within their work, it is useful to group guidelines together to known design concepts. The defining of the design categories and the clustering of the guidelines to the categories is done by the author of this thesis and researchers from the Institute of Production Science and Management. Therefore, the arrangement has its

[137] Marshall, pp. 2–3

[138] Huang 1996, p. 70

[139] Andreasen *et al.* 1983, pp. 84–138

[140] Corbett *et al.* 1991, pp. 114–117

[141] Kuo *et al.* 2001, p. 245

[142] Anderson 1997, pp. 234–239

[143] Anderson 2004, pp. 232, 257-262

[144] Marshall, pp. 2–3

[145] Corbett *et al.* 1991, pp. 51,54

[146] Krause and Kipp 2008, pp. 428–431

[147] Siddique *et al.* 1998, pp. 4–5

limitations. It is possible to define other design categories or allocate guidelines differently. Nevertheless, this classification should help to get a better overview of the 60 guidelines.

Therefore, four design categories are formulated, which allows to cluster the individual guidelines:

- **Standardization** aims at simplifying the processes and physical parts at different product levels. The reduction of part variety and production steps is the primary goal of this category. 17 guidelines can be allocated to this design category.
- **Modularity** includes all guidelines, which aims at clustering parts into groups in order to reuse them more often. Design for Variety provides the majority of the principles for this category.
  Modularity contains 10 guidelines from the whole catalogue.
- **Handling and Joining Guidelines** aim at the manufacturing process. Herewith, the focus is to provide easy assembly steps for the production stuff.
  Design for Assembly has a main impact on this category and it contains 23 guidelines.
- **General Guidelines** describe the last design category. All guidelines, which cannot allocated to the previous categories or have a common goal, belong to this category.
  The last 10 principles are allocated to this category.

6.1.3 The Final Catalogue

This catalogue serves for the next steps as a primary overview of the main guidelines within the product design stage. An extract of the final catalogue can be seen in Figure 31. For the detailed catalogue, see Appendix A.

Nr.	Qualitative Design Guidelines
1	Use standard components
2	Use catalog parts
3	Decompose cost-intensive components with a huge amount of variants to standard and variant components
4	Use of proven components, specify quality parts from reliable sources
5	Design parts to be multi-useable
6	Standardise design parameter (geometry, material …) of different variants (e.g. raidius/depth ratio of a drilling hole)
7	Use overdesign to avoid product variants (e.g. make filling tanks larger than necessary)
8	Avoid right/left parts, Use Paired parts for twice the quantity and half the number of parts
9	Maximize part symmetry e.g. square part, drilling holes with same distances from each other
10	Minimize the number of parts
11	Minimize the needs for special tools
12	Minimize Setups to reduce the production start time
13	Minimize Cutting Tools for machined produced parts, minimize cost by designing parts to be machined with the minimum number of cutting tools

Figure 31: Extract of the Design Catalogue

6.2 Evaluation of the Design Catalogue

In order to assess, which design concept or approach has an influence on the agility drivers, a first evaluation at different institutes of Graz, University of Technology is done.

Researchers from the university, who are working on the topic agility as well as on the product development process are asked to evaluate the design guidelines related to the influence on the four main agility drivers.

Seven researcher are from the Institute of Production Science and Management as well as from the Institute of Industrial Management and Innovation Research.

Two evaluations are done by members of the Institute of Machine Components and Methods of Development and one by the Institute of Automotive Engineering.

6.2.1 Method of Assessment

At first, the design catalogue is extended with the four agility drivers. Each guideline can be evaluated according to a pre-defined scale. The scale has five grades, which is related to the recommendation of Aschemann-Pilshofer:[148]

[148] c.f. Aschemann-Pilshofer 2001, p. 15

- “++” means that a guideline has a major positive impact on the specific agility driver.
- “+” means that a guideline has a minor positive impact on the specific agility driver.
- “-“means that a guideline has a minor negative impact on the specific agility driver.
- “--“means that a guideline has a major negative impact on the specific agility driver.
- 0 means that a guideline has no impact on the specific agility driver.

In order to assist the evaluator to assess the design catalogue, the template is pre-evaluated with no impact entries. These cells are marked with a grey background for an easier distinction. The rating of the gray marked cells is equal with a 0. Nevertheless, the rater can still revise the cells if it is thought, that the guideline has an impact on an agility driver.
For difficult to understand guidelines, pictures are provided, which illustrates the favourable and unfavourable design of the related guideline. Figure 32 shows an example of the provided additional information. This additional information is marked with a comment at the related guideline. The pictures are from the work of Krause and Kipp.[149]

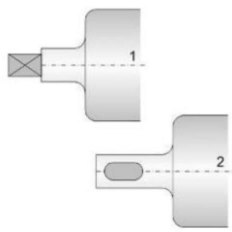
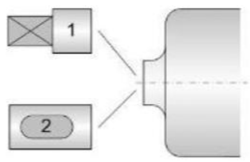
Description	Unfavourable	Favourable
Decompose cost-intensive components with a huge amount of variants to standard and variant components (e.g. roll flange)		

Figure 32: Example Favourable and Unfavourable Design[150]

In addition, the agility drivers are described with a short explanation as well as their influencing area within the simplified product life cycle (Figure 33).

[149] c.f. Krause and Kipp 2008, pp. 428–431

[150] Krause and Kipp 2008, p. 430

Idea		SOP	EOP
Simplified Product Life Cycle	Product Development Process		Production
	Product Design	Production Preparation	Production
Agility Driver		Late Changes	Diversity of Variants
	Time to Market		Quantity

Figure 33: Illustration of the Influencing Area of the Agility Drivers within the Product Life Cycle

An extract of the final evaluation template can be seen in Figure 34. For the detailed evaluation template, see Appendix B.

	Qualitative Design Guidelines	General Categories	Late Changes	Time to Market	Quantity	Diversity of Variants
1	Use standard components	Standardization				
2	Use catalog parts					
3	Decompose cost-intensive components with a huge amount of variants to standard and variant componen					
4	Use of proven components, specify quality parts from reliable sources					
5	Design parts to be multi-useable					
6	Standardise design parameter (geometry, material ...) of different variants (e.g. raidius/depth ratio of a drilling hole)					
7	Use overdesign to avoid product variants (e.g. make filling tanks larger than necessary)					
8	Avoid right/left parts, Use Paired parts for twice the quantity and half the number of parts					
9	Maximize part symmetry e.g. square part, drilling holes with same distances from each other					
10	Minimize the number of parts					
11	Minimize the needs for special tools					
12	Minimize Setups to reduce the production start time					
13	Minimize Cutting Tools for machined produced parts, minimize cost by designing parts to be machined with					
14	Minimize costs related to Drawings and Documentation, e.g digitalization, use of CAD					
15	Minimize the number of assembly movements					
16	Minimize the number of assembly directions					
17	Avoid separate fasteners, reduce the number of Bolts, or replace bolts by a snap lock					

Figure 34: Extract Evaluation Design Catalogue

After the evaluation the scale is converted into numbers in order to calculate the average results. “++” is converted to 2, “+” to 1, “-“ to -1 and “--“ to -2.

6.2.2 Results of the Internal Evaluation

At first, the average impact of all guidelines on the individual agility driver is calculated. Therefore, the individual score of each rater is summed up and divided by the number of guidelines and evaluator.

The highest score for that comparison is 2, whereas the lowest is -2. The result shows that all guidelines have the most impact on the agility driver Quantity with an average score of 0.55 (Table 2).

Table 2: Impact of all Guidelines on Specific Agility Driver

	Agility Driver			
Evaluator	Late Changes	Time to Market	Quantity	Diversity of Variants
1	0.53	0.20	0.77	0.53
2	0.42	0.15	0.80	0.53
3	0.28	0.25	0.35	0.50
4	0.28	0.22	0.32	0.42
5	0.17	0.05	0.88	0.30
6	0.20	0.28	0.42	0.12
7	0.25	0.15	0.60	0.13
8	0.22	0.28	0.50	0.38
9	0.12	0.22	0.57	-0.05
10	-0.12	0.35	0.27	-0.18
Average	0.24	0.22	0.55	0.27

Diversity of Variants with 0.27 and Late Changes with 0.24 are the next two most influenced agility drivers. Lastly, Time to Market can be influenced at least by all guidelines (0.22).

The next investigation is, which design category has the most impact on the agility drivers in general. The highest score for that comparison is 8 due to the sum of the highest score of each individual agility driver, which is 2. The lowest score is -8.
For that comparison it is assumed that each agility driver has an equal importance (Table 3). The result shows that modularity with a score of 1.78 have the most impact on agility. The next category is standardization with a score of 1.74, followed by the general guidelines with 1.40. Handling and joining guidelines have the least impact on the agility (0.78).

Table 3: Impact of the Individual Design Category on Agility

	Design Categories			
Evaluator	Standardization	Modularity	General Guidelines	Handling and Joining Guidelines
1	2.71	2.70	2.50	1.04
2	2.41	3.00	2.00	1.00
3	2.06	3.20	1.10	0.22
4	2.65	1.70	0.90	0.13
5	0.76	2.80	2.10	0.96
6	1.41	1.20	0.80	0.74
7	2.03	2.10	1.35	1.43
8	2.18	1.20	1.20	0.96
9	0.88	0.30	0.90	1.04
10	0.35	-0.40	1.10	0.26
Average	1.74	1.78	1.40	0.78

If these two tables are combined, it can be assessed, how big the impact of each design category on the individual agility driver is.
Table 4 illustrates the result of that comparison. The highest score for that comparison is 2 whereas the lowest is -2.

Table 4: Influence of Each Design Category on the Individual Agility Driver

	Agility Driver			
Design Categories	Late Changes	Time to Market	Quantity	Diversity of Variants
Standardization	0.33	0.48	0.64	0.30
Modularity	0.62	0.15	0.29	0.73
General Guidelines	0.24	0.38	0.47	0.31
Handling and Joining Guidelines	0.03	0.00	0.70	0.05

Following are some of the core statements of this evaluation:

- With modularity, the agility driver’s Late Changes and Diversity of Variants can be influenced.
- Handling and joining guidelines have almost only a positive effect on the category Quantity.
- Although the guidelines have been rated individually, the design categories standardization as well as handling and joining guidelines have the biggest influence on the agility driver Quantity.

Generally, no design category influences the agility drivers negatively. This effect can be explained with the formulating of the individual guidelines (See Chapter 4.2.5). The researchers try to express the guidelines in a way, that the recommendations have only a positive effect on the design. This approach can be seen in the investigation. Just one scientist rated one design category negatively.

6.3 Formulation of a Design Recommendation Catalogue

As the evaluation is done with each individual design guideline, it can be investigated, which guidelines have the most impact on an agility driver.

The comparison ranks the guidelines according to the different agility areas and deliver the best lever for each driver. This helps companies, who want to focus on a specific agility area, to have a pre-ranking with the best approaches.

This ranking for each agility lever is called design recommendation catalogue. To create this catalogue the average impact of each guideline on the individual agility driver is calculated.

The design recommendation catalogue is divided into the four agility drivers. The ten highest ranked design guidelines are shown for each agility driver in the Figure 35, Figure 36, Figure 37 and Figure 38.

- **Late Changes**

Qualitative Design Guidelines	General Categories	Average
Use software instead of hardware solutions to create product variants	General Guidelines	1.650
Decompose cost-intensive components with a huge amount of variants to standard and variant components	Standardization	1.350
Use standard components	Standardization	1.250
Changing one product characteristic should not effect more than one module	Modularity	1.250
Design module interfaces compatible	Modularity	1.150
Use catalog parts	Standardization	0.950
Use overdesign to avoid product variants (e.g. make filling tanks larger than necessary)	Standardization	0.950
Assign every function directly to one module of the product	Modularity	0.950
Use additional elements to create geometric variants (e.g. size variant of a role)	Modularity	0.950
Assign every variant product characteristic directly to one module	Modularity	0.850

Figure 35: Top Ten Guidelines to Influence Late Changes

- **Time to Market**

Qualitative Design Guidelines	General Categories	Average
Use standard components	Standardization	1.750
Use catalog parts	Standardization	1.650
Use of proven components, specify quality parts from reliable sources	Standardization	1.550
Minimize Setups to reduce the production start time	Standardization	1.150
Several methods to develop a robust and error free product and to develop the right product. Quality function deployment (QFD), Failure modes and effect analysis (FMEA), Taguchi methods, Problem-solving techniques	General Guidelines	1.150
Develop a modular design (for products where modules make sense)	Modularity	1.050
Understand manufacturing problems/issues of current/past products	General Guidelines	1.050
Process selection; Define manufacturing processes, which are appropriate for the quantity and the existingproduct design, e.g. Welding vs. Casting vs. Bolts etc.	General Guidelines	0.850
Design parts to be multi-useable	Standardization	0.750
Decompose cost-intensive components with a huge amount of variants to standard and variant components	Standardization	0.650

Figure 36: Top Ten Guidelines to Influence Time to Market

- **Quantity**

Qualitative Design Guidelines	General Categories	Average
Raw material selection; Select a material which is easy available and avoid rare materials. Use material, which is easy to operate with machines	General Guidelines	1.650
Use catalog parts	Standardization	1.250
Develop a modular design (for products where modules make sense)	Modularity	1.250
Process selection; Define manufacturing processes, which are appropriate for the quantity and the existing product design, e.g. Welding vs. Casting vs. Bolts etc.	General Guidelines	1.250
Use standard components	Standardization	1.150
Avoid right/left parts, Use Paired parts for twice the quantity and half the number of parts	Standardization	1.050
Minimize the needs for special tools	Standardization	1.050
Provide simple handling and transportation	Handling Guidelines	1.050
Avoid the possibility of assembly errors including Poka-Yoka Techniques	Handling Guidelines	1.050
Minimize Setups to reduce the production start time	Standardization	1.000

Figure 37: Top Ten Guidelines to Influence Quantity

- **Diversity of Variants**

Qualitative Design Guidelines	General Categories	Average
Use software instead of hardware solutions to create product variants	General Guidelines	1.350
Develop new product variants based on a non-order-related variant	General Guidelines	1.350
Design parts to be multi-useable	Standardization	1.150
Design module interfaces compatible	Modularity	1.150
Use parallel and serial configurations to create perfomance variants (e.g. battery configuration, parallel to increase current, serial to increase voltage)	Modularity	1.150
Manual assembly offers great flexibility towards: various product types, component variantions, faulty components, unforeseen assembly problems	Handling Guidelines	1.050
Variant characteristics without any effect on the function should be isolated in new cost-efficient components (e.g. cell phone color)	Modularity	0.950
Develop a modular design (for products where modules make sense)	Modularity	0.850
Assign every function directly to one module of the product	Modularity	0.850
Assign every variant product characteristic directly to one module	Modularity	0.850

Figure 38: Top Ten Guidelines to Influence Diversity of Variants

7 Expert interviews

In order to evaluate which concepts are used within the companies, interviews with several experts are held. Furthermore, the created design recommendation catalogue approach is evaluated related to the applicability in the industry. The interviews are held with experts, which have experience on product design or product development. These experts should preferential be head of the product development or have several years of experience within that area.

The companies are sought out by the condition having a design department as well as a production site within their business. This guarantees that the experts have experience in both areas. To narrow the investigated industry field, the companies are chosen within the mechanical engineering area.

Generally, it is possible to group companies into several classifications. Schlegel provides several characteristics in which production companies can be ordered.[151]
For this thesis, the companies will be classified by the major characteristic; type of manufacturing. Within this category, companies are categorised by batch size low (<20), middle (20-1000) and high (>1000).
Due to the limited interview amount, companies with batch size low and middle are grouped together in order to extend the individual results within this categorisation.

Twelve companies have been contacted and asked for an interview about their design approach within the company, as well as the importance of agility.
Nine companies replied with a positive answer. One of them doesn’t have a design department and is therefore not suitable for the evaluation.

[151] c.f. Schlegel A. 2002, p. 18

7.1 Company Description

From the eight selected companies, two companies request to stay anonymous due to data privacy. It is allowed to use their input in the work, but not name or allocate the results to the specific company.
Therefore, the two anonymous companies are just described roughly without naming them, whereas the other companies will be named and described in detail. One expert requests to stay personally anonymous, however it is allowed to mention the company's name.

7.1.1 Magna Steyr

Magna Steyr is an automotive supplier with roughly 10,000 employees worldwide. The range of services of Magna Steyr covers from vehicle contract manufacturing, engineering services up to fuel systems. The interviewed expert is working within the development department and has project management and product positioning experience from previous jobs at Daimler Chrysler and Audi.

7.1.2 Ventrex

Ventrex is an Austrian company with place of business in Graz. I currently employs around 150 people. The company develops and produces diverse valves for Compressed Natural Gases powered vehicles. Furthermore, the company produces compressors for tires as well as for seats. The export rate of Ventrex is 100 per cent, the customers are mostly located in Germany.
The expert is head of the product development and from R&D Department at Ventrex.

7.1.3 Knapp

The Austrian company Knapp is located in Hart bei Graz and provides warehouse automation and warehouse logistics systems. Their warehouse systems are used for storage articles like pharmaceuticals, fashion, cosmetics and retail. Knapp has currently around 2,500 employees.
The interviewed expert of Knapp is director of product management and responsible for the worldwide positioning and development of their products.

7.1.4 Palfinger Marine

Palfinger Marine is a subsidiary company of Palfinger AG and offers offshore solutions. In their product portfolio cranes, recovery systems, boats and wind cranes are available. They currently employs around 650 people.
The experts of Palfinger Marine request to stay anonymous and are from the project management and the quality department.

7.1.5 Liebherr

Liebherr is a Germany based company with a location in Bischofshofen, Austria. Some of the biggest divisions of Liebherr are earth moving equipment, mining equipment, cranes, machine tools and deep foundation machines.
The site in Bischofshofen is responsible for the global development and production of wheel loaders. The company has in total around 40,000 employees, around 1000 of them are working in Bischofshofen.
The expert is head of the development of wheel loaders at Bischofshofen.

7.1.6 Kristl, Seibt und Co. GmbH

Kristl, Seibt und Co. GmbH (KS) is a manufacturer of test benches and testing equipment for several automotive OEMs. Furthermore, industrial automation solution as well as building facilities are provided. Roughly, 400 people are currently employed.
The interviewed expert is head of the design department and an experienced product development manager.

7.1.7 Anonymous Companies

The first anonymous company is operating within the automotive sector, supplies several OEMs and has more than 10,000 employees. The interviewed expert of that company is global head of product development and responsible for the mechatronic systems of all developed products.
The second anonymous firm is worldwide active, has more than 10,000 employees and has several business divisions. The expert from the company is an experienced product development manager and is working within the automotive supplier section.

7.2 Method of Assessment

The aim of the interviews is to get information about the used concepts as well about the importance of agility within the company. The method low abstracted interview is used, which is described by Töpfer.[152]
The interviews have a main structure, nevertheless the individual dialogue is held flexible according to the situation. The frame of the interviews is defined in advance in order to cover the main ideas and desirable incomes of the interviews. Therefore, main questions are formulated in advance. It is desired to be able answering all of the pre-defined questions at the end of the interviews.

After the interview a two page summery is written, which is sent to the experts to review the conversation. This should guarantee that the content is understood correctly. The summery of expert interviews can be seen in Appendix B.

7.2.1 Expert Interview Template

The template, which serves as a frame for the expert interview, has five sections. The interview starts with an introduction and with a clarification of the main terms. Next, questions about product design, agility in general and the importance of the pre-defined agility drivers are asked. After that, it is investigated, which product design concepts are used to increase the agility and the derived drivers. The last section contains the applicability of the design catalogue.

7.2.2 Introduction and Clarification

The first sections contains general questions and information. It is asked if the company and the interviewed persons wish to stay anonymous. Furthermore, the aim of the thesis and basic terms, like agility, are described in detail.
In order to unify and to have the same understanding of the different product design and product development process concepts, the concepts, Design for X, Delayed Product Differentiation, Set Based Design, Front-Loading and Simultaneous Engineering are explained to the experts.

[152] c.f. Töpfer 2012, pp. 244–245

Lastly, it is pointed out that the design catalogue is based on Design for Manufacturing, Design for Assembly and Design for Variety guidelines.

7.2.3 Questions about Product Design

The second section contains the question about the product design and product development process concepts, which are used by the companies. At first, it is asked which Design for X concepts are used conscious and unconscious, e.g. through general design knowledge, by the designers or themselves. The next question asks which of the other mentioned and not described concepts are used for designing products. The last question in this section includes on which design concepts the companies want to focus in the future.

7.2.4 Questions about Agility

The third section covers the topic agility. At first, the four agility drivers Late Changes, Time to Market, Quantity and Diversity of Variants are explained in detail. Furthermore, their affected area within the product development process is illustrated. Examples should help to understand the difference and the problems of the drivers.

After that, the importance of agility for the company is asked. If an experts states, that agility is not importance, the reason behind that decision is evaluated. If agility is relevant for the expert, the significance of the pre-defined agility drivers is asked.
The experts have to rate the agility drivers according to the importance for their company. The rating is done as followed:

- The value 2 means that this driver has a high importance for the company. It will be strongly focused to increase the possibility to influence this area.
- The value 1 means that this agility driver has a low importance for the company. It will be minor focused to increase the possibility to influence this area.
- The value 0 means that this driver has no importance for the company. Within the company it is not focused react to changes for the respective area.

Lastly, it is asked if the expert thinks of other agility areas or criteria, which are also essential related to product design.

7.2.5 Questions about the Combination of Product Design and Agility

The fourth section covers the interaction between the product design concepts and the agility drivers. The first question asks if within the company product design concepts are used to influence the agility. If so, further detailed investigations, about which concepts have the biggest influence or importance for the individual agility drivers, are done. The last question of this section asks, on which product design concepts the company wants to focus in order to increase their agility in the future.

7.2.6 Evaluation of the Design Catalogue and the Ranking of Guidelines for Each Agility Driver

After the company related discussion, the focus of the last part is the evaluation of the design catalogue and the derived best guidelines for each agility lever by the expert.
At first, the aim and the structure of the catalogue is described and the four design categories, standardization, modularization, general guidelines as well as handling and joining guidelines are explained to the experts.
After that, the internal evaluation results of the design catalogue are presented to the experts and the design guideline recommendations for the agility drivers are described.
It is asked how the design catalogue can be implemented within the company and how the approach would look like. Finally, the strengths, weaknesses, opportunities and threads of the design catalogue are asked.

7.3 Results of the External Evaluation

After the interviews the results of the companies are grouped related to their production volume. As above described, it is distinguished between companies with high and low production volume.
The two anonymous companies, Magna Steyr, Ventrex, and Liebherr are allocated to the group with high production volume, whereas Knapp, Palfinger Marine and KS belongs to the low production volume group.

7.3.1 Results of Design Concepts

At first the used product design concepts of all companies are compared and represented in a table. This allows an overview of all implemented concepts within the companies (Table 5).

Table 5: Design Concepts Comparison of all Companies

	Companies							
	High Production Volume					Low Production Volume		
Concepts	Anonymous	Magna Steyr	Ventrex	Anonymous	Liebherr	KNAPP	Palfinger Marine	KS
Standardization	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Modularisation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Design for Assembly	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Design for Manufacturing	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Design for Variety	Yes					Yes	Yes	
Design for Switchability			Yes	Yes	Yes		Yes	
Delayed Product Diff.				Yes		Yes		
Set Based Design						Yes		
Simultaneous Engineering	Yes	Yes	Yes	Yes	Yes	Yes		
Frontloading	Yes	Yes	Yes	Yes		Yes		Yes
Design to Costs			Yes	Yes		Yes		Yes
Design to Value				Yes		Yes		
FMEA	Yes			Yes				

In this table it is exemplified that every company is already implementing a standardization and modularisation concept. The experts expressed that nowadays this is crucial to be competitive and to reduce costs. Furthermore, the internal part as well as assembly variety can be decreased.

Furthermore, Design for Manufacturing and Design for Assembly guidelines are state of the art of every company and guarantee low costs and high quality of the manufactured products. The approach Design for Variety is more focused by companies, which have a low production volume and offer individual products. The experts from companies with high production volume declared that they already have to define their product portfolio at the beginning of the development process.
Design for Switchability is used by four companies. These experts stated that it is tried to consider alternative materials within the product design process. One scenario is to change to another material if the first choice is not available due to supply chain issues.
The scenario, that the raw price of the preferred material increases and therefore switching to a different cheaper material, is not consciously considered by the experts. This results that the designers unconsciously use this approach in more ways to react agile.

The product development process concepts, Simultaneous Engineering and Front-Loading are the main approaches to shorten the development time and to detect potential problems already very early in the development progress. The design concept delaying the product differentiation is just used by two companies. Furthermore, set based design is just done by one company. The expert explained that the focus within their company is to detect possible errors and to define the products early in the development process. Working on several solutions at the same time is just done at the beginning of the concept phase and not during the whole development process.

Further design concepts and focus, which are not stated or defined in this thesis but mentioned by the companies are Design to Costs, Design to Value and Failure Mode and Effects Analysis (FMEA).
The approach Design to Costs is used by three companies and has the focus to reduce the part and assembly costs. One expert explained that at a specific mature stage of the product model Design to Cost is used to tackle explicit the production costs.
Design to Value is mentioned by two companies, which is a design concept to recognise and deliver more precisely customer's requirements. The experts explain that this approach further contains the Design to Costs approach, nevertheless adds the customer's wishes better in the design process.

The Failure Mode and Effects Analysis is explicit mentioned by two companies. This approach has the goal to avoid later faults through early identification and evaluation of potential error sources. It is tried to fulfill these preventive measures very early in the development process and to include the improvements into the product design.

7.3.2 Importance of Agility for the Companies

All companies declared that being agile is nowadays an important topic for them. The experts explain that they face a volatile market and agility is an important approach to stay competitive as well as to react more efficient to unexpected events. Just one experts declared that the derived agility drivers are not that important for their business.

As agility is explained to the interviewed people it is observed that other terms are often used. The term “Flexibility” or “Dynamic” is used to describe every possibility to react to changes. They extend the influence area than described in the literature, nevertheless regarding the purpose the same understanding of agility is demonstrated.

The next step of the experts is to rate the agility drivers according to the importance for their company. The rating is done as described above.
Table 6 shows the ranking of the agility driver for companies with high production volume. The average of each agility driver is calculated to get a better overview.

Table 6: Importance of the Agility Drivers for Companies with High Production Volume

Agility Drivers	Anonymous	Magna Steyr	Ventrex	Anonymous	Liebherr	Average
Late Changes	0	0	1	0	0	0.20
Time to Market	2	2	0	2	0	1.20
Quantity	0	2	1	0	1	0.80
Diversity of Variants	0	0	1	1	0	0.40

Time to Market is the most important agility driver for the five companies. Most of the experts state that offering products faster to the market allows a competitor’s advantage and it reduces the possibility that other companies bring their product faster to the market.

The second most important agility driver is Quantity. This should cover the possibility of sales fluctuations within the companies. One expert states that better forecasts helps to hinder this driver.

Late Changes and Diversity of Variants have a minor role for the companies. Two experts state that the product portfolio are already determined at the beginning of the product development stage and is not changed or added afterwards. Late Changes from customers can only occur until a special defined design freeze.

Table 7 illustrates the importance of the agility drivers for the three companies with low production volume.

Table 7: Importance of the Agility Drivers for Companies with Low Production Volume

Agility Driver	Knapp	Palfinger Marine	KS	Average
Late Changes	1	1	2	1.33
Time to Market	0	0	1	0.33
Quantity	0	0	0	0.00
Diversity of Variants	2	2	1	1.67

For them the highest importance is the driver Diversity of Variants. The experts state that it is often necessary to create new variants from existing products very quickly. Knapp and Kristl, Seibt und Co. GmbH explained that every product of them is mostly unique and tailored to the requirement of the customers. For Knapp the used modules of their new products are already available, nevertheless around 10 to 20 per cent of the whole product has to be developed new. Therefore, a new product variant of the existing modules has to be developed very quickly.

The second most important driver is Late Changes. The companies have continually to deal with changes during the product development process. The experts of Knapp, Palfinger Marine and KS explained that they are working very closely with their customer and already know that the clients often change their requirement during the development. Therefore, it is important to react better to that requirement.

Time to Market and Quantity are not the focus for the companies with low production volume. The reasons for that are diverse.
Quantity is not important due to the fact that most products of Knapp and KS are unique, therefore the batch size is one. Also for Palfinger Marine quantity is not important as they just produce in batch sizes for one project and especially for one customer. Therefore, they do not have to adapt to sales fluctuations. In cases of an increasing production volume, Palfinger Marine gets help from its parent company Palfinger AG.

Time to Market is also not that important for the three companies as their order related projects determine the date of delivery. All three experts state that it is not helpful if they develop the projects after the project started faster than arranged. On the example wind mill, which are operated offshore, Palfinger Marine explained that a too early installation as required have counter-productive effects, because the product already gets signs of wear and tear.

If the two company groups are compared in respect to the importance of the agility drivers followed conclusion is made. The investigated companies with high production volume are more focusing on Time to Market as well on Quantity whereas the investigated companies, which have a low production volume, especially want to focus on Diversity of Variants followed by Late Changes (Table 8).

Table 8: Importance of the Agility Drivers for Companies with High and Low Production Volume

	Late Changes	Time to Market	Quantity	Diversity of Variants
High production volume	0.20	1.20	0.80	0.40
Low production volume	1.33	0.33	0.00	1.67

7.3.3 Design Concepts to Influence the Agility Categories

Table 9 illustrates the focus of design concept in order to increase the agility within the companies.

Table 9: Design Concepts to Improve Agility

	Companies							
	High Production Volume					Low Production Volume		
More Focus on	Anonymous	Magna Steyr	Ventrex	Anonymous	Liebherr	KNAPP	Palfinger	KS
Standardization	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Modularisation	Yes	Yes	Yes	Yes		Yes	Yea	Yes
Design for Assembly								
Design for Manufacturing								
Design for Variety						Yes		Yes
Design for Switchability			Yes	Yes	Yes		Yes	
Delayed Product Diff.								
Set Based Design								
Simultaneous Engineering			Yes	Yes				
Frontloading	Yes		Yes	Yes		Yes		

After the questioning it is noticed that every of the investigated company want to focus further on standardization. The experts stated that they see high potential that this approach further reduce the complexity and support their company to react easier and faster to external changes.

The interest focusing on modularisation is stated by seven experts. They mentioned that due to shorter product cycle they have to reduce the developing time. Special emphasis on modularisation helps them to create new variants faster and with less development effort. Furthermore, the experts stated that modular design allows them to react more agile as the changing affected assemblies and parts are lower than with an integral design. The expert of Palfinger Marine explained on the example marine cranes, which are mostly individually developed for one project, that further emphasis on modularisation helps them to reduce the development effort and increase the quantity of the individual assembly.

None of the investigated companies want to focus in the future on Design for Assembly and Manufacturing as these approaches are already well implemented within their companies.
Knapp and KS are focusing on the approach Design to Variety. They stated that due to their priority to improve on the agility drivers Late Changes and Diversity of Variants, Design for Variety is the best concept to react specific on that requirement.

Four companies want to focus in the future on the concept Design for Switchability. They explained that other materials than the preferable one are very important to consider within the product design. Within the company Liebherr the switch of materials is possible to a limited extend, e.g. between different steel materials.
For Palfinger Marine this approach is also important if suppliers of special materials have delivery problems, therefore this approach supports them at supply disruptions.

None of the investigated companies want to focus in the future on the concepts Delayed Product Differentiation and Set Based Design. The experts stated that Set Based Design is difficult to implement. Furthermore, Delayed Product Differentiation is not their focus to react faster to changes.
Simultaneous Engineering is an approach, which two companies are focusing in order to support the agility driver Time to Market.

Four experts stated that within their company they will focus in the future on the design concept Front-Loading. For Ventrex and the two anonymous companies this approach guarantees that the agility driver Time to Market is being improved due to shorter development time. Furthermore, it allows to define and evaluate the first concept of the product more precisely.

Table 10 outlines the concepts, on which the companies with low and high production volume are focusing to improve their stated agility drivers, which are illustrated in Table 8.

Table 10: Design Concepts and Other Concepts of Companies to Influence the Individual Agility Categories

	Late Changes	Time to Market	Quantity	Diversity of Variants
High production volume		Simultaneous Engineering, Frontloading	*Agile Manufacturing and Labor*	
Low production volume	Design for Variety			Design for Variety

If more than 50 per cent of the companies are focusing on the same concept to influence the same agility driver, the concept is included in the table.

The investigated companies, which have a high production volume, focus on Simultaneous Engineering and Front-Loading to influence Time to Market.
Furthermore, to influence the quantity the interviewed experts explicit mention that they cover this driver with agile manufacturing and labor than with specific design concepts.

Of the investigated companies, which have a low production volume, the approach design for variety is used to react to Late Changes and Diversity of Variants.

7.3.4 Applicability of the Design Recommendation Catalogue

The last point of the interview was to evaluate the applicability of the design catalogue. Seven experts stated that the design catalogue is in general a very good approach to call attention on the possibility how to influence the agility drivers by product design. The catalogue illustrates many of the basic guidelines within one list.

On the other hand six experts explicit mentioned that the catalogue with the guidelines is too common to implement directly on a product. The catalogue has to be adapted or more specified according to the product, to the applied area or to the size of the company. Furthermore, the knowledge of the individual designer of the companies should be considered and included into the catalogue.

In general five experts have interest to implement this design catalogue within their company and would further specify the catalogue for their needs. One expert stated that the catalogue can be used as a checklist at the individual milestones of their product development process. Nevertheless, it has to be defined which guideline is used at a specific design phase.

7.4 Conclusion of the Expert Interviews

In general, the evaluation of the design concepts shows that concepts like Design for Manufacturing and Assembly are already well established within all interviewed companies. Furthermore, it can be seen, that companies do not want to further focus on this approach to improve their agility.

Furthermore, seven out of eight companies declare that agility is a major topic for them, whereas the focus of the pre-defined agility drivers is different for companies with high or low production volume. Furthermore, for their individual agility demands, the companies are focusing on different design concepts.

Companies with high production volume focus on the agility drivers' Quantity and Time to Market. Demand fluctuations are mainly covered within agile production systems and labor, whereas Time to Market will be improved by the concepts Simultaneous Engineering and Front-Loading.
In comparison, the companies with low production volume want to improve Late Changes and Diversity of Variants. To support this requirement they want to focus further on the Design for Variety approach.

In general, all companies want to focus on the approaches modularity and standardization in the future. Both approaches should decrease the development and manufacturing costs as well the internal part variety. Furthermore, they should improve the agility in general within the companies.

In order to evaluate the generated design catalogue in detail and to compare the results with the internal evaluation, case studies are done with companies, which have an interest to implement the catalogue within their business.
These case studies are described in Chapter 8.

8 Case Studies

In order to evaluate the formulated design catalogue with companies, case studies are accomplished. As above described five companies have an interest to implement the design catalogue within their business.
From these five, three companies are selected for the case studies due to having specific situation in which the design catalogue can be applied. These companies are Ventrex, Kristl, Seibt und Co. GmbH and Knapp.

At first, the method of assessment is described, followed by an explanation of the initial situation of the different companies as well as the results of the case studies. The last point suggests a method how to implement the design catalogue within companies.

8.1 Method of Assessment

Each case study of a company consists of two main parts.

At first the initial situation of the company is described. Furthermore, a product is selected and the structure of it is described. On this product, the design catalogue is applied and it is evaluated, which concepts are already implemented by the company.
Furthermore, the desired agility driver of the situation is defined. The rating of the experts is related to this driver and is compared with the internal evaluation.

The second part consists of the actual rating of the design catalogue and all mentioned guidelines. For this reason, the design catalogue is modified with three rating sectors in order to enable a proper evaluation (Figure 39).
The first sector asks for the already implementation of the design catalogue. The evaluator can set a ‘x’ if this guideline is already in usage.
The next three columns differentiate between the usefulness of the specific guideline. One the three choices has to be chosen; is useful, has to be adapted or more specified to use or not useful.

The last sector includes the rating of the guideline, the rating score is the same as for the internal evaluation (see 6.2.1).
In the last column comments can be made in order to give additional hints or suggestions.

		x = Yes; Empty = No	Choose One of the Three Choices; x = Yes, Empty = No			Rating see bottom left	
	Qualitative Design Guidelines	**Already in use**	**Is useful**	**Has to be adapted or more specified to use**	**Not useful / applicable**	**Your Rating**	**Comments**
1	Use standard components						
2	Use catalog parts						

Figure 39: Case Study Rating Template

8.2 Interpretation of the Evaluation

With the evaluation four main points are covered:

1. At first, the general applicability of the design catalogue is investigated. This illustrates if the guidelines can be used on the product anyway.

2. Secondly, it is investigated, which guidelines are not used yet, however have the possibility to improve the design to react more accurate to the desired agility driver. These guidelines are compared with the internal rating.

3. Furthermore, the general score difference between the company and the internal rating is calculated. This allows an assessment how accurate the internal rating can be used for a general statement.

4. Lastly, it is investigated, if the catalogue can be shortened. Guidelines, which have after the internal and the external evaluation a lower rating score than 0.5 the guideline can be neglected. This gives the advantage to illustrate the main guidelines for the individual agility driver.

8.3 Case Study Ventrex

The first case study is done with the company Ventrex as they have an interest to implement the design catalogue. At first the initial situation of Ventrex is described, followed by the results of the case study.

8.3.1 Initial Situation

As Ventrex is already a provider of assemblies it is directly focused on a specific product. With the cooperation of Dr. Jaritz the investigated product is an electrical gas pressure regulator for compressed natural gas (CNG) cars. This module regulates the pressure of a CNG from a tank of 260 bar to a variation of 2-12 bar before the injection. A picture of this product can be seen in Figure 40.

Figure 40: Electrical Gas Pressure Regulator

The situation for Ventrex was to increase the quantity from 25000 to an amount of 100000 pieces within the year 2014. This lead to the requirement to focus on supporting the production. Therefore, the agility driver for the product electrical gas pressure regulator is Quantity.
It is investigated how the design catalogue could have supported the demand for Ventrex.

8.3.2 Results

At first the design catalogue is evaluated in general. Following pie chart illustrates the applicability of the design catalogue (Figure 41):

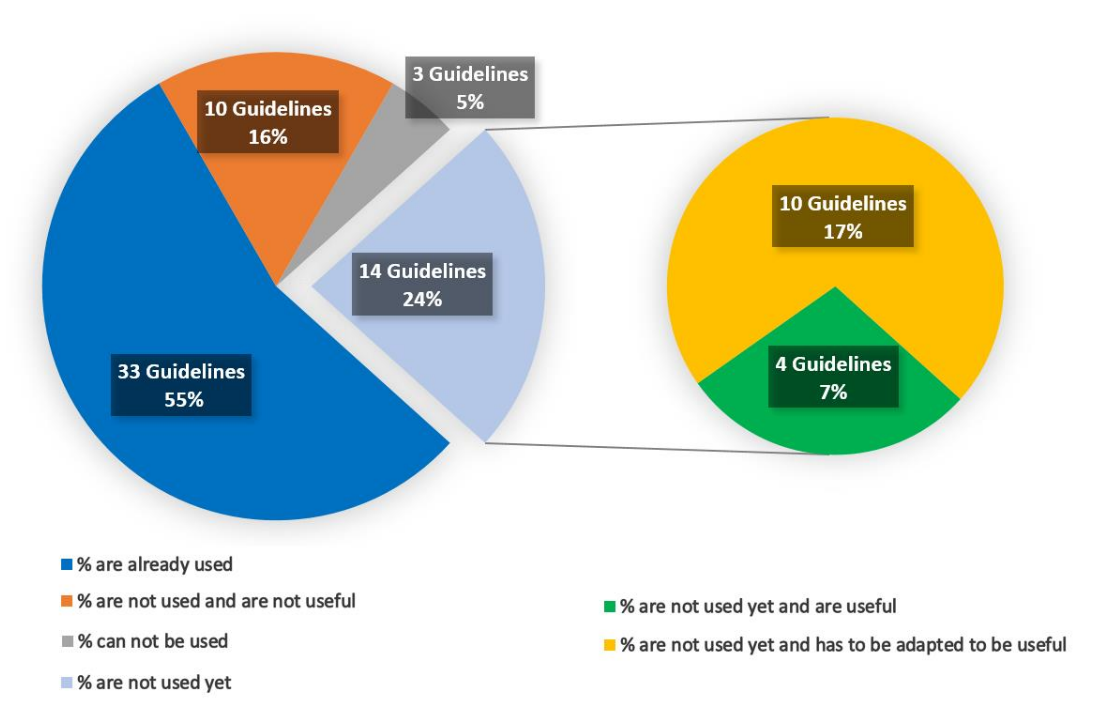


Figure 41: Analysis of the Design Catalogue by Ventrex

- 33 guidelines of the design catalogue are already used for the product design and are useful or have to be more specified to be useful. This is equivalent to roughly 55 per cent of all guidelines.

- 10 guidelines of the design catalogue are not used for the product and are not useful. This is equivalent to roughly 16 per cent of all guidelines.

- 3 guidelines of the design catalogue cannot be used for the product design because the guidelines are not applicable on the product. This is equivalent to roughly 5 per cent of all guidelines.

- 14 guidelines of the design catalogue are not used for the product but are useful or have to be more specified to be useful. This is equivalent to roughly 24 per cent of all guidelines.

The last 14 guidelines will be more investigated in detail as these guidelines have according to Ventrex the possibility to improve their design and to react more accurate to the quantity driver.
Four of them can be used directly on the product design, whereas the other 10 have to be more specified for use (see Figure 41, right side).

Table 11 illustrates the comparison of the directly useful guidelines between the internal and the company evaluation. Two of them are included in the design recommendation (Figure 37) and have nearly the same internal and external rating score. The other two guidelines have an internal rating score of 0.45 and 0.35. They are more important for Ventrex than after the internal rating.

Table 11: Comparison Internal and Ventrex Rating of Helpful Guidelines related to Quantity

	Quantity	
Guideline	**Internal**	**Ventrex**
Provide simple handling and transportation	1.05	1
Avoid right/left parts, Use Paired parts for twice the quantity and half the number of parts	1.05	1
Distinguish different parts that are shaped similarly thorough no geometric means	0.45	1
Provide easy access for locating surfaces, symmetrical parts or exaggerate asymmetry	0.35	1

To extend this comparison, the internal and external rating of the whole design catalogue is compared in general. Table 12 shows the similarities between the ratings, the average result is at Ventrex a just little bit lower.

Table 12: Comparison of the Design Categories Rating related to Quantity

	Quantity	
Design Categories	Internal	Ventrex
Standardization	0.64	0.41
Modularity	0.29	0.10
General Guidelines	0.47	0.60
Handling Guidelines	0.70	0.57
Average:	0.53	0.42

By comparing the internal and external rating of each guideline, for 47 guidelines or roughly 75 percent the rating score of is lower or equal than one note difference (See Appendix C). This illustrates the high correlation between the internal and external rating related to quantity.

The last part of the case study investigates if the design catalogue can be shorten. The comparison shows that 12 guidelines have in both ratings a lower score than 0.5, therefore the catalogue for the agility driver quantity can be shortened to 48 guidelines (see Appendix C).

8.4 Case Study Kristl, Seibt und Co. GmbH

The second case study is done with the company Kristl, Seibt und Co. GmbH. At first the initial situation of Kristl, Seibt und Co. GmbH is described, followed by the results of the case study.

8.4.1 Initial Situation

For Kristl, Seibt und Co. GmbH, which is a provider of automotive testing equipment, the initial situation comes from the requirement of providing individual solutions for the customer.
Some of their products are full vehicle test benches, where several driving conditions are simulated (Figure 42). These products consist of several modules, one of them is the driving unit, which simulates the resistance for the tyres (Figure 43).

Figure 42: Vehicle Test Bench

As KS is working closely with the customers, their need is to react accurate and fast to modifications from customers throughout the whole product development process. Therefore, the agility driver Late Changes is chosen to cover this demand. It is evaluated, how the design catalogue could support this situation.

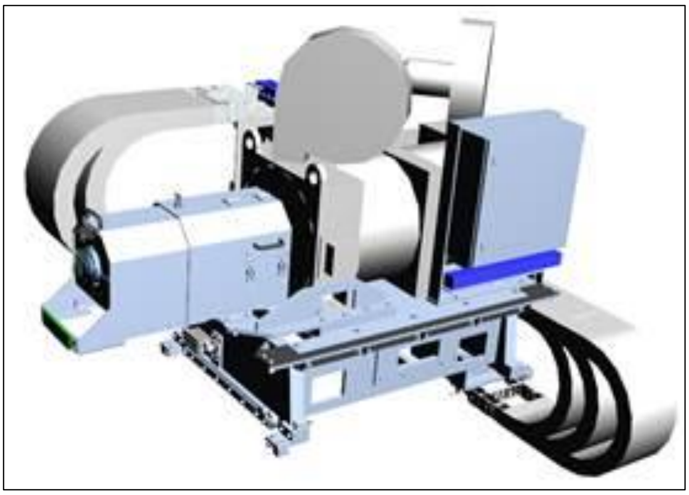


Figure 43: Driving Units

8.4.2 Results

The pie chart in Figure 44 illustrates the applicability of the design catalogue on the investigated product, driving unit:

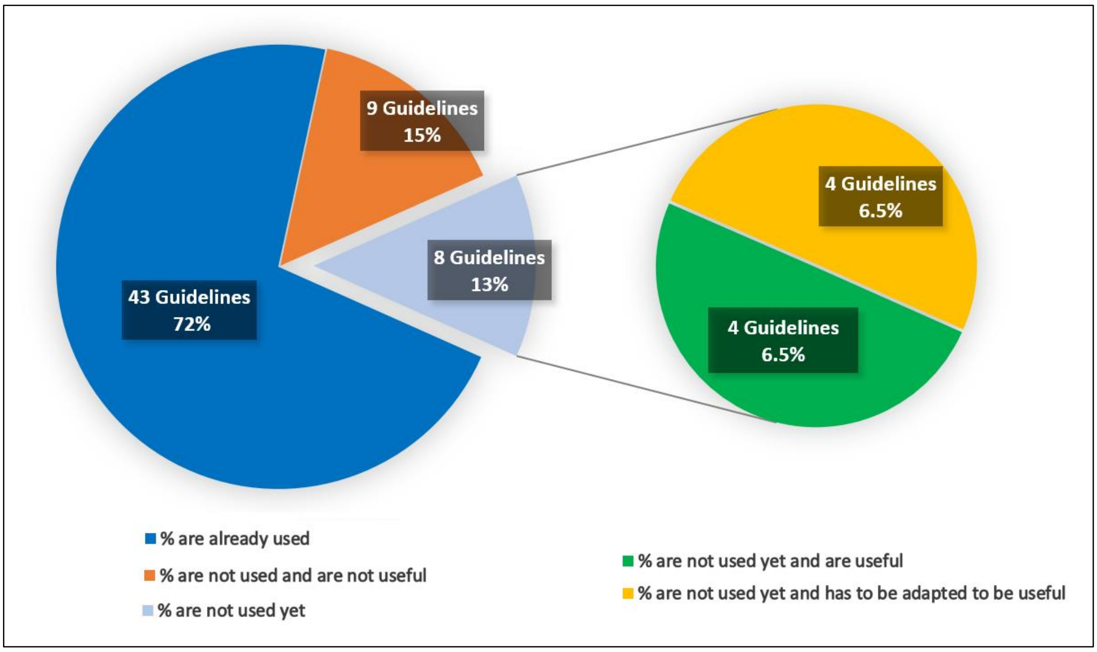


Figure 44: Analysis of the Design Catalogue by Kristl, Seibt und Co. GmbH

- 43 guidelines of the design catalogue are already used for the product and are useful or have to be more specified to be useful. This is equivalent to roughly 72 per cent of all guidelines.
- 9 guidelines of the design catalogue are not used for the product and are not useful. This is equivalent to roughly 15 per cent of all guidelines.

- 8 guidelines of the design catalogue are not used for the product but are useful or have to be more specified to be useful. This is equivalent to roughly 13 per cent of all guidelines.

The last 8 guidelines have the opportunity to improve the design of the driving unit. Four guidelines can be applied directly whereas the other four have to be more specified for the usage (see Figure 44, right side).

In Table 13 the rating score comparison of these four guidelines between the internal and external evaluation is illustrated. Also, in this case study two guidelines of them are included in the design recommendation for late changes (Figure 35). However, one guideline has according to the internal rating no influence on Late Changes, which is different evaluated by KS.

Table 13: Comparison Internal and KS Rating of Helpful Guidelines related to Late Changes

	Late Changes	
Guideline	Internal	KS
Decompose cost-intensive components with a huge amount of variants to standard and variant components	1.35	2
Changing one product characteristic should not effect more than one module	1.25	1
Use cut to fit modularity to create geometric variants (e.g. size variant of a role)	0.65	1
Provide easy access for locating surfaces, symmetrical parts or exaggerate asymmetry	0	1

To extend this investigation, the internal and external rating of the whole design catalogue is compared in general. Table 14 demonstrates that the average rating score of KS is roughly four times higher than the internal one. This lead to the assumption that for KS the guidelines have a higher impact on the product than through the internal rating.

Table 14: Comparison of the Design Categories Rating related to Late Changes

	Late Changes	
Design Categories	Internal	KS
Standardization	0.33	1.41
Modularity	0.62	1.10
General Guidelines	0.24	1.20
Handling Guidelines	0.03	1.26
Average:	0.30	1.24

Comparing the internal and external rating of each guideline, it turns out that 34 or roughly 55 per cent of all guidelines have been rated less or equal one note difference (See Appendix C). This is the result of the higher average score of KS. Therefore, the internal rating has its limitation on this case study due the huge rating difference.

The last investigation of the case study is, if the design catalogue can be shorten. The comparison shows that 9 guidelines have in both ratings a lower score than 0.5. Therefore, related to the agility driver Late Changes, the design catalogue can be shortened to 51 guidelines (see Appendix C).

8.5 Case Study Knapp

The last case study is done with the Knapp as they also showed and interest to implement the design catalogue. At first the initial situation of Knapp is described, followed by the results of the case study.

8.5.1 Initial Situation

For Knapp, which is a provider of warehouse logistic systems, a new product system is the “Pick-it-Easy Shop”. It is especially developed for handling heavy items with different tall containers. In order to guarantee ergonomic situation for the worker, various heights are compensated by the system. The containers are filled manually by the stuff (Figure 45).

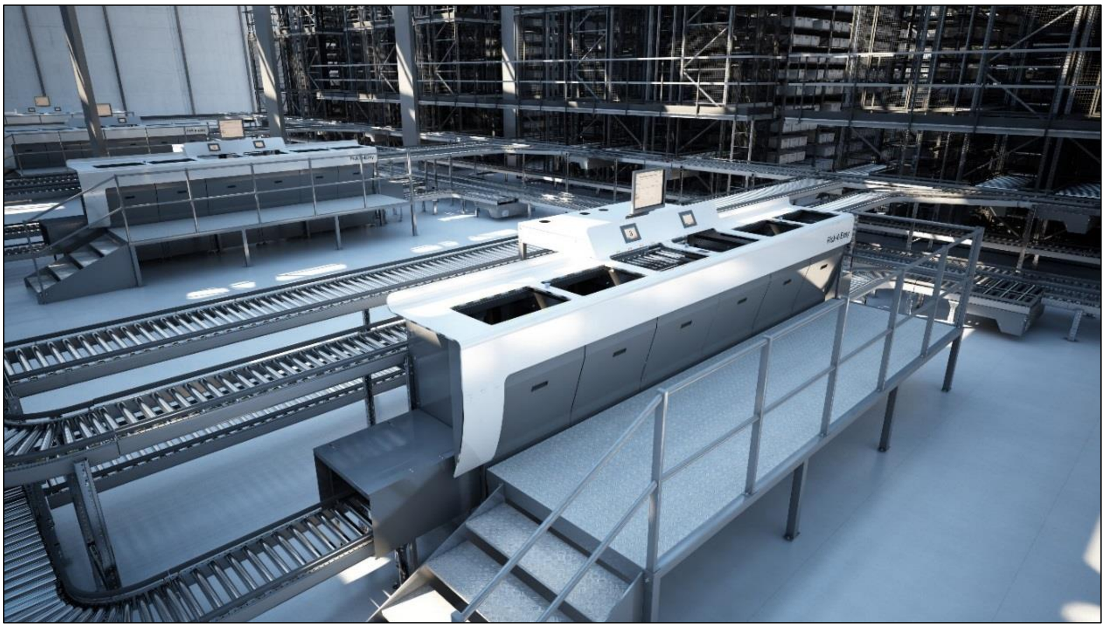


Figure 45: Pick It Easy Work Place

Through the modular structure this workplace can be used for different requirements (Figure 46).

For Knapp the agility driver Diversity of Variants is very important because each variant has to be developed individually.

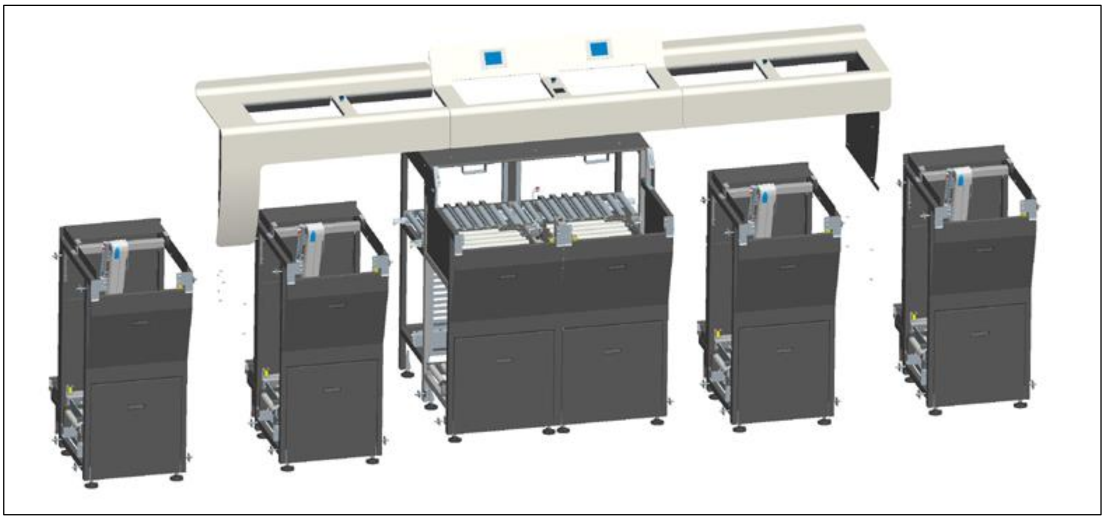


Figure 46: Modular Design of the Pick It Easy Shop

8.5.2 Results

Following pie chart illustrates the applicability of the design catalogue for the "Pick It Easy Shop" (Figure 47):

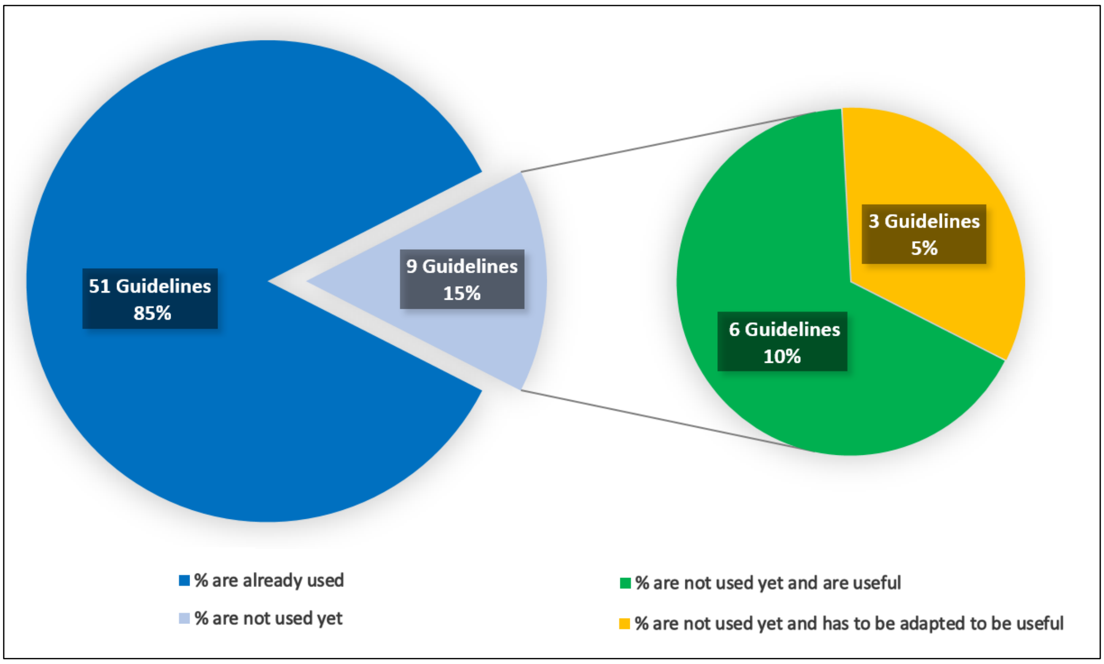


Figure 47: Analysis of the Design Catalogue by Knapp

- 51 guidelines of the design catalogue are already is use and are useful or have to be more specified to be useful. This is equivalent to roughly 85 per cent of all guidelines.

- 9 guidelines of the design catalogue are not used yet for the product but are useful or have to be more specified to be useful. This is equivalent to roughly 15 per cent of all guidelines.

- None of the guidelines cannot be used. This results from the complexity of the product. It has several sub-assemblies and parts, therefore lots of diverse manufacturing and assembly steps are available.

The 9 guidelines, which are not used yet and are useful, will be investigated in detail.

Six of them can be used directly on the product design, whereas the other 3 have to be more specified in order to be used (see Figure 47, right side).

The comparison of the internal and external rating score of this 6 directly useful guidelines is illustrated in Table 15. Two are already in the design recommendation catalogue (Figure 38) as they have a high internal rating. Nevertheless, the huge difference of other 3 guidelines, which have an internal score of 0, shows that the expert uprate these approaches.

Table 15: Comparison Internal and Knapp Rating of Helpful Guidelines related to Diversity of Variants

	Diversity of Variants	
Guideline	**Internal**	**Knapp**
Develop new product variants based on a non-order-related variant	1.35	1
Variant characteristics without any effect on the function should be isolated in new cost-efficient components (e.g. cell phone color)	0.95	1
Changing one product characteristic should not effect more than one module	0.75	2
Several methods to develop a robust and error free product and to develop the right product. Quality function deployment (QFD), Failure modes and effect analysis (FMEA), Taguchi methods, Problem-solving techniques	0	2
Proper spacing ensures allowance for a fastening tool	0	2
Design for automatic assembly in order to achive uniform assemblies, few erroneous assemblies, uniform high quality and great system reliability	0	2

The general comparison of the design categories, which is seen in Table 16, outlines that the rating of Knapp is significant higher. This lead to the assumption that for Knapp the guidelines have a higher impact on the product compared to the internal rating.

Table 16: Comparison of the Design Categories Rating related to Diversity of Variants

	Diversity of Variants	
Design Categories	Internal	KNAPP
Standardization	0.30	2.00
Modularity	0.73	1.30
General Guidelines	0.31	1.70
Handling Guidelines	0.05	1.48
Average:	0.35	1.62

The comparison of the individual guidelines illustrates that only 23 or roughly 40 per cent of all guidelines have been rated less or equal one note difference (See Appendix C). This observation matches with Table 16 as the average rating score for KNAPP is considerably higher.

Lastly, it is investigated if the design catalogue can be shorten. Although, after the internal rating 44 guidelines have a lower score than 0.5, most of these guidelines have a positive impact for Knapp. Only one guidelines has in both rating a low score. Therefore, it is suggested that the design catalogue should not be shortened (see Appendix C).

8.6 Case Study Conclusion

The case studies demonstrate the usefulness and limitation of the design catalogue.

It is shown that all three companies could identify guidelines within the catalogue, which are not used yet and have the possibility to support their agility demand.
Nevertheless, many guidelines, which are not used yet, have to be adapted or more specified to use. This results from the general expression of the guidelines.

The next observation is that the rating of the internal and external are quite diverse. The Ventrex case study shows that the comparison of the rating score is quite similar. Though, the KS and Knapp case study illustrate that the rating can also be quite different. Therefore, the internal rating has to be considered with its limitation as the internal rating is done at the university.

Shortening the design catalogue has also its limitation. Through the case studies the results are not uniform. The recommendation for companies is to individually screen through the design catalogue in order to identify the relevant guidelines for them.

8.7 Approach to Implement the Design Catalogue

The design catalogue and the derived recommendation catalogue should highlight the potential of several product design concepts on agile manufacturing.
As Design for Manufacturing, Design for Assembly and Design for Variety are covered, the design catalogue can be used as a tool to monitor, if the basic guidelines of DFX are already implemented. Furthermore, the derived design recommendation catalogue can serve as a list to highlight the most important guidelines for each agility area. This supports designers to include agility aspects and the importance of this topic into the design process in order to react more accurate to changes.

The response from the expert interviews and through the case studies outline that several companies have a high interest to use this catalogue as a tracking tool. After analysing the weaknesses and opportunities of the expert interviews it turned out that the design catalogue has to be adapted, before it can applied to a company.

Figure 48 illustrates a method how to use the design catalogue within a company.

1. At first the agility area, in which the company want to react faster to changes, has to be defined. As the guidelines have a diverse influence on the different agility drivers, this is a crucial step. Nevertheless, the company can also focus on more than one agility area.

2. Furthermore, a person or department has to be determined, which is responsible for the usage of the catalogue. From the feedback of the experts, it is suggested that the quality department should take over the charge.

3. The next step is to screen and modify the catalogue to the needs of the companies. As the guidelines are expressed in a general way, a workshop with experienced designers, quality department and management should ensure that the guidelines are adapted to the company’s situation. Furthermore, the expressed guidelines should be

highlighted with favourable and unfavourable design examples, which are tailored to the company.

4. An important step is to introduce and explain the design catalogue to all designers, who are working in the company. This should guarantee that the catalogue is not an imposition for the designers. The advantage as well as the limitations of the catalogue should be explained and illustrated to the designer.

5. The last point is the continual improvement of the catalogue. After each project the catalogue should be revised during the lessons learned workshop. This should guarantee that the catalogue includes the latest insights of the designers. Furthermore, it encourage the knowledge transfer between different design departments.

The illustrated approach should support companies to implement the design catalogue and to highlight the importance of agility during the design stage.

Nevertheless, it has to be considered that companies may already have a design catalogue or a design method installed within their company. For this circumstance, the guidelines and the results should be integrated in the existing tool.

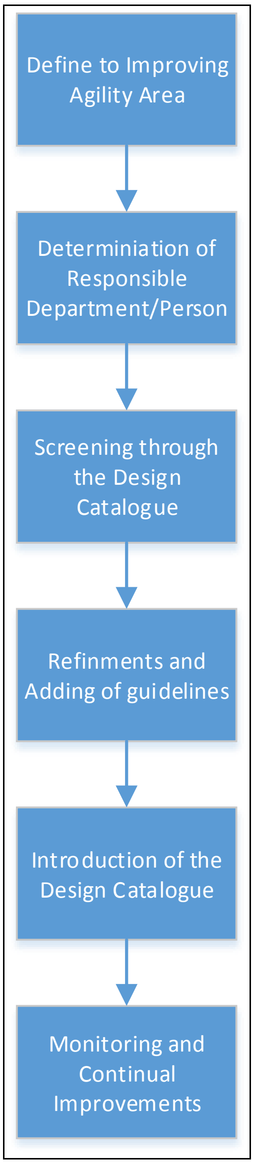


Figure 48: Approach to Implement the Design Catalogue

9 Conclusion and Outlook

In chapter one, the importance of the product design has been outlined. It is a complex, nevertheless an important stage during the product development process in which the success of a later produced product is determined. On the one hand, the duration of the development, and on the other hand the commitment of later incurred costs makes this stage very important. An increasing degree of volatility makes the design phase an important lever to accurately react to changes. Furthermore, the objectives of the thesis have been outlined.

In Chapter 2, the product design stage and the overall product development process have been explained. Furthermore, different product architecture types are described in detail. Finally, a literature review of several definition of agile manufacturing is provided.

After that, the investigated concepts have been collected and categorised into the used product development stage. Simultaneous Engineering, Front-Loading, Set Based Design, and Delayed Product Differentiation are occurring during the whole development process (Chapter 3), whereas the Design for X approach is used within the product design stage (Chapter 4).

In order to evaluate the concepts related to their impact, four agility drivers, Late Changes, Time to Market, Diversity of Variants and Quantity, have been defined. On these drivers, the influence of product design have been further investigated (Chapter 5).

In Chapter 6 a design catalogue, which combines several Design for X approaches, has been created. A first evaluation of the design catalogue to influence the four agility drivers was made by several researchers who are currently working on the topics of product design or agility. With this evaluation, it has been illustrated that the design categories influences the agility drivers strongly different.
While modularity has a main impact on Late Changes and Diversity of Variants, handling and joining guidelines have almost only a positive effect on the driver Quantity. Furthermore, it has been discovered that almost every

researcher positively rated the influence of the design category on the agility drivers. This correlates with the formulation of the guidelines within the literature. It is tried to express the guidelines in a way, that the recommendations have only a positive effect on the design.
Based on that evaluation, a design recommendation catalogue for each agility driver has been derived. This catalogue supports companies to focus on a specific agility area by having a pre-ranking with the best approaches.

To investigate the usage of the concepts within the industry, expert interviews with eight companies have been carried out. The firms have been divided into companies with high and low production volume. After the evaluation, it was able to allocate different agility requirements for the two groups (Chapter 7).
The companies with low production volume want to improve Late Changes and Diversity of Variants. To support this requirement they want to focus further on the approach Design for Variety.
In comparison, the investigated companies with high production volume have a desire to react more accurate on the agility drivers Quantity and Time to Market. Demand fluctuations are mainly covered within agile production systems and labor, whereas Time to Market will be improved by Simultaneous Engineering and Front-Loading.
All companies declared that their general design focus will be on standardization as well as on modularisation. Both approaches should support agility in general as well as the internal part and assembly variety should be decreased. Furthermore, the development as well as the manufacturing costs should be decreased by both approaches. The interviews also demonstrated that Design for Manufacturing and Assembly approach is well implemented, though not the focus in the future to improve agility.

Based on the expert interviews, case studies are accomplished for further investigation of the design catalogue. (Chapter 8). Three companies have been selected and a situation, which demonstrates the need of agility, is determined. Furthermore, a product is selected on which the design catalogue has been applied. The results showed the applicability and the limitations of the design catalogue. At each case study, it was able to find guidelines which are not implemented yet but have a positive influence.

However, many guidelines have to be adapted before usage as they have been formulated in a too general way.
Furthermore, the comparison of the internal and external rating score showed the limitation of the design recommendation catalogue. For two companies, the guidelines had more importance, therefore their rating score was significant higher. The last point investigated, if the design catalogue can be shortened. Through the case studies, the results are not uniform. The recommendation for companies is to individually screen through the design catalogue in order to identify the relevant guidelines for them.

After the interviews, it was recognized that the catalogue may get to an imposition for the designers. Therefore, a method how to implement the design catalogue has been provided. The approach should help companies with the implementation of the design catalogue.

Outlook

There are several further research potentials on this topic. At first, the external investigation can be done with more companies. This should guarantee that the knowledge of other industries are also covered and included.

Furthermore, the design catalogue can be extended with more concepts and guidelines. The applicability of the design catalogue on concepts like Simultaneous Engineering, Front-Loading, Set Based Design, and Delayed Product Differentiation has to be investigated.

Another research topic is to include the costs within the design approaches. It should be investigated how much the budget should be for a design approach based on the financial impact of the ability to react more accurately to changes at a later state.

List of Abbreviation

DFA	Design for Assembly
DFM	Design for Manufacturing
DFMA	Design for Manufacturing and Assembly
DFV	Design for Variety
DFX	Design for X
DMU	Digital Mock Ups
DPD	Delayed Product Differentiation
EOP	End of Production
FEM	Finite Element Methods
FMCG	Fast Moving Consumer Goods
FMEA	Failure Mode and Effects Analysis
JIT	Just in Time
KS	Kristl, Seibt und Co. GmbH
NPD	New Product Development
OEM	Original Equipment Manufacturer
PDP	Product Development Process
QFD	Quality function Deployment
SOP	Start of Production
SPC	Statistical Process Control
TQM	Total Quality Management

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Appendix A Design Catalogue

Nr.	Qualitative Design Guidelines	Design for Assembly	Design for Manufacture	Design for Variety	Number of mentions	General Categories
1	Use standard components	x	x	x	3	Standardization
2	Use catalog parts		x		1	
3	Decompose cost-intensive components with a huge amount of variants to standard and variant components			x	1	
4	Use of proven components, specify quality parts from reliable sources	x	x		2	
5	Design parts to be multi-useable	x	x		2	
6	Standardise design parameter (geometry, material ...) of different variants (e.g. raidius/depth ratio of a drilling hole)			x	1	
7	Use overdesign to avoid product variants (e.g. make filling tanks larger than necessary)			x	1	
8	Avoid right/left parts, Use Paired parts for twice the quantity and half the number of parts		x		1	
9	Maximize part symmetry e.g. square part, drilling holes with same distances from each other	x	x	x	3	
10	Minimize the number of parts	x	x		2	
11	Minimize the needs for special tools	x	x		2	
12	Minimize Setups to reduce the production start time		x		1	
13	Minimize Cutting Tools for machined produced parts, minimize cost by designing parts to be machined with the minimum number of cutting tools		x		1	
14	Minimize costs related to Drawings and Documentation, e.g digitalization, use of CAD	x			1	
15	Minimize the number of assembly movements	x			1	
16	Minimize the number of assembly directions	x			1	
17	Avoid separate fasteners, reduce the number of Bolts, or replace bolts by a snap lock	x	x		2	
18	Develop a modular design (for products where modules make sense)	x	x		2	Modularity
19	Design module interfaces compatible			x	1	
20	Assign every function directly to one module of the product			x	1	
21	Assign every variant product characteristic directly to one module			x	1	
22	Variant characteristics without any effect on the function should be isolated in new cost-efficient components (e.g. cell phone color)			x	1	
23	Changing one product characteristic should not effect more than one module			x	1	
24	Use parallel and serial configurations to create perfomance variants (e.g. battery configuration, parallel to increase current, serial to increase voltage)			x	1	
25	Use cut to fit modularity to create geometric variants (e.g. size variant of a role)			x	1	
26	Use additional elements to create geometric variants (e.g. size variant of a role)			x	1	
27	Integrate one component with another so that: difficult handling is avoided, critical positioning or inlaying is avoided and the total number of operations is reduced	x			1	

Nr.	Qualitative Design Guidelines	Design for Assembly	Design for Manufacture	Design for Variety	Number of mentions	General Categories
28	Several methods to develop a robust and error free product and to develop the right product. Quality function deployment (QFD), Failure modes and effect analysis (FMEA), Taguchi methods, Problem-solving techniques	x	x		2	General Guidelines
29	Optimize Toleranzes and Surfaces, like as approximate as possible and as exact as necessary		x		1	
30	Use software instead of hardware solutions to create product variants			x	1	
31	Understand manufacturing problems/issues of current/past products		x		1	
32	Develop new product variants based on a non-order-related variant			x	1	
33	Product variety should be created in the end of the assembly process			x	1	
34	Raw material selection; Select a material which is easy available and avoid rare materials. Use material, which is easy to operate with machines		x		1	
35	Process selection; Define manufacturing processes, which are appropriate for the quantity and the existingproduct design, e.g. Welding vs. Casting vs. Bolts etc.		x		1	
36	Adhere to specific process design such as welding, casting, forging, etc. E.g. For casting avoid cavities, provide radii, etc.		x		1	
37	Design for fixturing		x		1	
38	Provide simple handling and transportation	x	x		2	Handling Guidelines
39	If part symmetry is not possible, make parts very asymmetrical and provide orienting features to avoid assembly error		x		1	
40	Provide easy access for locating surfaces, symmetrical parts or exaggerate asymmetry	x			1	
41	Insert new parts into assembly from above	x			1	
42	Provide suitable lead-in chamfers for easier assembly	x			1	
43	Provide alignment features	x			1	
44	Design open enclosures	x			1	
45	Design parts so that they are easily oriented	x			1	
46	Distinguish different parts that are shaped similarly thorough no geometric means	x			1	
47	Avoid visual obstructions	x			1	
48	Avoid simultaneous fitting operations	x			1	
49	Avoid parts which will tangle or nest	x			1	
50	Avoid adjustments which affect prior adjustments	x			1	
51	Avoid the possibility of assembly errors including Poka-Yoka Techniques	x			1	
52	Place fasteners from obstructions, fasteners should be easily accessible	x			1	
53	Provide flats for uniform fastening and fastening ease	x			1	
54	Proper spacing ensures allowance for a fastening tool	x			1	
55	Guide pins shall be provided for alignment of modules or high-density connectors	x			1	
56	Design for automatic assembly in order to achive uniform assemblies, few erroneous assemblies, uniform high quality and great system reliability	x			1	
57	Manual assembly offers great flexibility towards: various product types, component variantions, faulty components, unforeseen assembly problems	x			1	
58	Components should be able to withstand high-speed mechanical handling	x			1	
59	Components should be free from oil or swarf	x			1	
60	Use 'magazines', a mechanical form or frame which parts or wholly maintains the components in a constant orientation	x			1	

Appendix B Expert Interview Summaries

Expert Interview with Dr. Gerald Jaritz

Company VENTREX, 3.2.2015

General Product Design Concepts

Dr. Jaritz explained that VENTREX like many of the supplier in the automotive section uses the A, B, C, and D samples to describe the developing progress of their prototypes and products. Which design concepts is used is related to the different stages. For the A-sample the main concept is Design to Function. For the B-sample it is extended to Design to Cost, furthermore during this stage the material and manufacturing process are determined. After the B-sample there is a design freeze of the product. All later changes are complicated and cost intensive. For the C-sample the Design for Manufacture and Assembly concept is used.

To avoid doing past errors again VENTREX design engineers use an internal design catalogue, in which main guidelines and lessons learned experiences are included. This document is continuously further developed.

The basic design approaches within VENTREX are Modularisation and Standardization. Furthermore, it is aimed to allocate the function of a product specific to the physical parts.

Furthermore, basic Design to Switchability concepts are used due to the increasing quantity during the product life cycle.

For the evaluating and improving of the product design virtual engineering and prototyping are applied.

Lastly, morphological matrices are used to combine the required functions of the product with different characteristics/options. This gives a good overview of the possible solutions.

Agility and the derived Drivers

Agility is in general very important for VENTREX. Internally, the definition flexibility and dynamic are used to describe the ability to react fast to unforeseen changes. The measures are also proactive therefore the basic approaches of agility can be compared with the VENTREX synonyms. One advantage to react fast is having all competences (Design department, production) within one location. Therefore, the process of prototyping and getting a feedback from the production can be done very fast, which gives a benefit to larger companies.

For VENTREX all agility drivers are generally significant. Nevertheless, the driver time to market plays for VENTREX a minor importance. Due to the role of VENTREX as a supplier the schedule is given by the automotive manufacturer.

In general it is tried to reduce the changes as much as possible. The reason is mainly due to the resulting costs. Furthermore, lean principles are implemented within VENTREX.

Product Design Concepts to increase Agility

Within VENTREX the main approach to react fast to changes is using the predefined morphological matrix. This table helps to have alternative design concepts already visible if changes are necessary. Furthermore, Modularisation and Standardisation help on the one hand to simplify the variants of product designs on the other hand if parts are used again it reduces the development effort.

The importance of Design of Switchability for Agility is demonstrated from Dr. Jaritz by the example of producing a seal. Instead of machining and using an expensive material in the beginning of the product life, it should be possible to switch to a cheaper material and a large-scale production process like injection molding if the number of parts are increasing shortly. This reduces the cost tremendous.

Within VENTREX it is tried to recognise future trends as soon as possible and to implement future solutions already very early into their product. Furthermore, stakeholders can change specific requirements very fast. One example from Dr. Jaritz are emission regulations, which are mainly determined by the government or European Union and can occur very fast.

Furthermore, Dr. Jaritz mentioned that the product life cycle also declines in their business and this results that prototyping has to be accomplished faster. Modularisation, the morphological matrix and simultaneous engineering support this.

Interim Evaluation of the design categories according to agility

Strengths:

Dr. Jaritz mentions that it helps to list basic approaches and it gives a good overview of the main design concepts. The design concepts (Modularisation, Standardization,…) are well defined and clear.

Weaknesses:

The basic objectivity is missing, due to the equal importance of the categories and the already evaluating from the research assistants.

Opportunities:

Dr. Jaritz suggests to evaluate the agility drivers with each other. This should help to get a better comparison and emphasis of the categories. Furthermore, sensitive analyses should help to see to what extend the ranking of the design guidelines is shifting.

Threads:

Lastly, if the structure is too complex it may result that companies are not using the catalogue.

Expert Interview with Roman Schnabl

Company KNAPP, 25.2.2015

General Product Design Concepts

Within Knapp Design for Assembly and Design for Manufacturing guidelines are used. Mr. Schnabl explained that it is an important that the designed components are producible easily within the own production line. Furthermore, the strategy 'Local for Local' should guarantee that the designed parts can be produced by the on-site fabrics, like America.

As KNAPP is a plant construction company for warehouses each final plant differs from the existing one. This lead to the focus on Design for Variety. Already used modules and parts are adopted to the new requirements.

Knapp are mainly using a modularisation strategy in order to build up the entire plant. Each main function is grouped into physical modules, like motor, band conveyer, etc. Each group has several different versions and the designers choose from the list of the different modules. Mr. Schnabl explained that each module from the different groups are compatible with each other, this guarantee a huge number of variations. Nevertheless, the bill of material is available for the entire plant at once and is adapting dynamically related to the modules.

This results that the final plant is unique whereas the assembly and structure in lower product levels are similar. The focus at the part level is on standardization and that carry over parts are used throughout the entire plant. This guarantee that the quantity of the individual parts are increased and the total number of individual parts are reduced.

To guarantee the easiness of adapting the individual changes, the design of the parts and assemblies are built on parameters in the CAD System. This helps to change the individual parts faster.

Another trend, which Knapp nowadays is facing, is Batch Size 1. As every customer has individual wishes, Knapp has to be able to provide customized solution.

Mr. Schnabl stated that Design for Switchability is not using as the costs of the manufacturing processes and raw material are not switching that much.

The Delayed Product Differentiation approach is mainly used within the software department.

Set Based Design helps in the first design stage, where the main components are chosen. The different design departments are working on several solutions and after a specific time the final solution is determined.
The focus in the future is on modularisation and platforms. This helps to reach easier the goal of Batch Size 1 and support to have common platforms with individual customized modules. The products are build either platforms or just grouped together with modules.

Agility and the derived Drivers

Agility in general is quite important for KNAPP as niche customers may provide better individual solution for special industries. KNAPP has more than 1500 customers in many different areas.
The necessity of KNAPP of providing individual systems is a result of no standardisation from the clients. Mr. Schnabl explained on the example clothes that each brand has individual boxes, which have to be transported and stored within logistic systems.
Therefore, the most important driver for KNAPP is Diversity of Variants. It is important to generate easily a new variant from existing modules as this reduce the development effort. The currently degree of individualisation is about 15-20% of a plant.
Mr. Schnabl explained that due to providing individual solutions for the customers the agility driver quantity is not relevant as no common plants are produced. Furthermore, late changes is the daily work for KNAPP as the customer' wishes are changing very often during the product development process.
The focus of KNAPP is to provide more easily variants and to reduce the development time tremendous. This should guarantee the competitiveness in the next years.

Product Design Concepts to increase Agility

KNAPP aims to reach higher agility with Modularisation and Standardisation. The approach of modularisation is to provide add-on modules for the customers. Mr. Schnabl explained on the example software that the clients just get and purchase the modules they need.
The goal of KNAPP is to focus more on Design for Variety guidelines as it crucial to derive a new plant very fast from the existing modules.

Design to Costs and Design to Value approaches are already established within KNAPP and not that important as the price of a plant has to be calculated for every project again.

Another tool in the future is virtual engineering. The software for each new plant can be simulated and emulated within a virtual environment. Furthermore, the interface to the client's software can be integrated and possible errors can be removed before it is actually tested on the real physical plant.

Interim Evaluation of the design categories according to agility

Strengths:

The catalogue lists the guidelines methodically and gives a good overview how to influence different agility categories.

Weaknesses:

The adverse consequences of the guidelines on the different agility drivers cannot been seen.

Opportunities:

The catalogue can serve as a supportive tool for KNAPP in order to list general guidelines and to improve the important agility drivers of KNAPP.

Threads:

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Expert Interview with N.N (Anonymous)

Company Palfinger Marine, 26.2.2015

General Product Design Concepts

For Palfinger Marine, which is a subsidiary company of Palfinger AG, cranes for a new project differ from the previous ones, therefore the company has to adapt new versions very quickly. The development and the production of the cranes are order-related. The manufacturing of Palfinger Marine is not in-house, the production is outsourced to Palfinger production facilities.
In general Palfinger Marine is using an assembly kit, therefore each product is divided into modules. Currently, the degree of modules are about 1/2. The goal for the future is to increase this further.
Standardisation and Carry over Parts should guarantee that a huge external variant of products can be offered whereas the internal variant is kept at a minimal spread.
Furthermore, Design for manufacturing guidelines are used. Palfinger Marine has standard for the processes like bending to ensure the easy manufacturability of the parts.

Agility and the Derived Drivers

In general agility is very important for Palfinger. Especially, the organization like number of personal has to be agile in order to react fast to changes.
Late Changes are in general common for Palfinger Marine, as the customer wishes may change during the product development process. Nevertheless, the changes can just occur up to a specific point. Changes at a later point makes it necessary to negotiate a new contract with the customer.
Time to Market is not that important for Palfinger as the order related projects determine the date of delivery. However it is important to minimize the lead time for customized projects.
N.N. explained on the example wind mill, which are operated offshore, that a too early installation as required have counter-productive effects. For the parent company Palfinger, which produces cranes for trucks, Time to Market means to have the product available when the truck is produced by the OEM.
Furthermore, the variation of the quantity are common for the company, this fluctuation is mainly compensated by the staff.

The most important driver is Diversity of Variants. It is significant to derive a new version from the existing modules as fast and cost efficient as possible.

Product Design Concepts to increase Agility

One design concept within Palfinger Marine to be agile is the usage of modules. For a standard crane the main product architecture is based on modules, sometimes a platform for several versions are used.
For cranes, which are just developed for one project, existing modules are used as much as possible. The differentiation should take place by changing just a few parts.
Furthermore, Design for Switchability approaches are used within Palfinger Marine. Alternative materials are listed, which supports the procurement if special materials are not available. Due to the cooperation with the parent company Palfinger metals can be obtained for a better price and therefore be used within the products of Palfinger Marine.
Furthermore, the switch between manufacturing processes guarantee that quantity fluctuations are better covered. N.N mentioned that competitors had problems with switching between welding and casting. As a result, Palfinger Marine is mainly focusing on welding in order to guarantee the quality.
New Innovative Solution for lifting concepts are monitored, nevertheless, N.N believes that the standard of the cranes are not switching within the next years. The construction for a standard marine hydraulic knuckle boom crane state of the art.

Interim Evaluation of the design categories according to agility

Strengths:
In general the results correspond with the experience of N.N.
Weaknesses:
The guidelines are too general for different companies, the industry specific adaption is missing. Furthermore, the scale should be clearer to understand.
Opportunities:
-
Threads:
The evaluation with just seven experts may be to less to have a convincing comparison of the different guidelines.

Expert Interview with N.N (Anonymous)

Company X, 27.2.2015

General Product Design Concepts

Depending on the product the guidelines Design for Manufacturing, Design for Assembly and Design for Variety are used within Company X. As an example, the main design approach for mechatronic systems is Design for Variety.

The portfolio of a new product is defined already in the concept phase. Consequently, the variants are developed parallel during the product development phase. Within the company X it is focused to find small number of scalable components of the product, which differs from variant to variant.

N.N explained this approach using the example of a brushless motor. The connector and the diameter of each motor are the same, the only different characteristic is the motor length, which determines the performance of the variants.

Within the company X, standardized design guidelines are defined based on internal and harmonized OEM standards. These guidelines reflect best practice as well as experience of designers. Furthermore, a FMEA analysis is state of the art within automotive industries to identify and eliminate design weaknesses systematically.

Currently, the product modularisation degree of the department of N.N is about 40 percentage with the target to increase this degree. Nevertheless, the internal variation of parts and modules should be decreased, the focus of this standardisation is especially at the assembly level.

A special focus is dedicated to the connector system, which represents a critical subsystem due to contact issues like vibration, intermittent load and many more. Due to harmonized standards for connector design, the design effort has reduced tremendously as OEMs, especially in EU and NA respectively, are using the same standardized component design.

Furthermore, Simultaneous Engineering is used to combine the knowledge of different departments are involved very early in the product development process.

Agility and the derived Drivers

To be agile is very important for the Company X as it increases the possibility to react to customer's wishes.
From the perspective of the magic triangle the main focus is to reduce the cost of a product. As important is the agility driver Time to Market. Offering products faster to the market allows a competitor's advantage. To keep the level of quality is mandatory anyhow.
Design changes before the milestone purchasing release are feasible, but the degree of the resulting change costs are increasing after design freeze through purchasing release. Nevertheless, late changes are not that usual as customers' requirements are well known from previous projects.
Using the example of a brushless motor, late changes could be done quite easily for scalable components like the housing or the population of the printed circuit board. Much more difficult are changes at the interfaces, especially, critical parts like connectors. These subsystems are very difficult to switch except there is just a reduction of transition performance with the same connector design.
The driver Diversity of Variants is not as important as Company X offers always at the beginning a product portfolio. N.N explained that nearly 80% of the main variants are already stated during the concept phase, the other 20% are results of individual customer's requirements.

Product Design Concepts to increase Agility

Within the Company X the main design approaches to increase the agility is Modularisation as well as Standardisation. Splitting up the product into modules should guarantee that the variants of different products can be build up by same modules.
To generate lots of carry over parts Design for Reuse guidelines are used. N.N. explained that especially at the assembly level it is important that modules can be used more often in order to decrease the development effort. Another interesting aspect is that the department of N.N also tries to reduce external variety as customer specific functionality and performance are a Unique Selling Proposition but not individual design.
An approach to shorten the development time is to use Front-Loading. This ensures that the product is developed before all requirements are known. In

future, Company X wants to focus on virtual engineering to ensure shorter development time.

Interim Evaluation of the design categories according to agility

Strengths:

N.N stated that in general the design guidelines are a good support for a company. It can support as a check list, which includes the general approaches.

Weaknesses:

It is very general and especially for company X the general guidelines has to be adopted to the specific products.

Opportunities:

Experienced designers can evaluate the catalogue and add their special knowledge to the list in order to guarantee a transfer of knowledge within a company.

Threads:

If the guidelines are too general it may not be used by companies.

Expert Interview with Ludger Weyers

Company Magna Steyr, 3.3.2015

General Product Design Concepts

Mr. Weyers explained that the Product Evolution Process for an automotive company is in general divided into three main stages.
The first stage is the Initial or Feasibility Phase, in which the Technical and Economic Feasibility is evaluated. The positioning of the product helps to allocate the different versions of a car into a model class, e.g. luxury class. An important topic is to define a Custom-Market profile, which includes comparing the new model with an existing, reference model.
The following stage is called Concept Phase. Within this phase the vehicle concept is developed. Front-Loading guarantees that problems and possible difficulties are detected and solved as soon as possible. Simultaneous engineering teams ensures that every area within the product is involved in the concept design to reduce the development time. The final result is a Target Agreement, in which all requirement of the new car are described and defined.
In the Series Development Phase the actual design of the components and modules takes place. The car is divided into groups and each design department is developing the components.
A main concept within every OEM is nowadays the platform strategy. The whole vehicle is divided into main modules, which some of them serves as a platform. These parts and modules are used along many model classes and brands.
Mr. Weyers explained that platforms, which are used in several car models have to resist the stresses and strains from the most demanding circumstances in any model, which is called platform variance.
The disadvantage of the platforms is the difficult differentiation for customers between similar car models. Another problem are product recalls, because the affected car quantity, which are using the same platform, are higher.

Agility and the derived Drivers

Mr. Weyers explained that late changes are only possible to a limited extend and should be avoided at any circumstances. The changes should mainly

occur within the initial phase. After this stage it is difficult and cost intensive to change. Furthermore, Engineering Change management are included in the process.
The most crucial driver is Time to Market. It is important to have all parts available at the right time in order to have no delays. A critical milestone is Start of Production, which has to be on track at any circumstances.
The quantity of the produced cars is increasing after the Start of Production until it reaches the production peak, which lasts about 3 months. This driver has therefore an importance due to sales fluctuations.
The variants of a product are already defined very early in the initial phase in order to set the boundary of the development effort.

Product Design Concepts to increase Agility

Mr. Weyers stated that the concept platform is used to increase the usage of carry over parts and modules in different car models. The trend of the OEMs is to increase the platform degree in order to reduce the development costs.
Changes of the production quantity are mainly covered within the production line.
Within the different OEM the changes after the SOP are done with facelifts. Technical improvements are combined with minor optical changes in order to extend the life cycle of a vehicle.

Interim Evaluation of the design categories according to agility

In general Mr. Weyers supports the internal evaluation and the results are conclusively with his experience.
Strengths:
The catalogue can support the internal checklist at the individual milestones.
Weaknesses:
The individual Design to X approaches are not timely ordered within the Product Development Process.
Opportunities:
Mr. Weyers explained that for a complex product like a vehicle, which has a long development process, the guidelines should be allocated to the different phases. This helps to have the right guidelines at the right time.
Threads:
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Expert Interview with Dr. Ing. Herbert Pfab

Company Liebherr, 9.3.2015

General Product Design Concepts

In general the construction vehicle at Liebherr are similar composed as automotive cars. There are several basic types, which determine the performance of the machines. Based on these types individual features can be add to fulfill the different customer wishes.
Liebherr uses several basic Design Concepts for their Products. The basic approaches of Modularisation and Standardisation are implemented.
Modularity ensures the reuse of assembly group as well as parts. Due to the growing diversity of external variety modularity reduces the development effort.
Furthermore, Standardization approaches, e.g. the use of carry over parts, increase the quantity of the individual parts. This will be done regularly in order to decrease the internal variety.

Agility and the derived Drivers

The derived Agility drivers are not that important for Liebherr due to following reasons.
Due to the extensive development effort, Late Changes are not occurring if the market or the customer requirements are changing. It is just important if the performance or functionality of the machines is not be reached. Changes after the order of the customer are problematic for the supply chain management to procure the changed parts on time.
The driver Time to Market is not be seen as the attempt to bring a new product faster to the customer. The development time and life cycle of a product are too long to react to these changes properly.
The main product portfolio is already determined at the beginning of the development stage, therefore the diversity of variants is not important after the development of the product. Only a few additional customer' related features may be developed after the product release.
Agility is required for reacting to changing markets and to new Innovation. Nevertheless, patents ensures that innovative solution is protected within the company.

Product Design Concepts to increase Agility

In general basic Design for Switchability approaches are implemented. The switch of materials is possible to a limited extend, e.g. between different steel materials. If the sales are increasing Liebherr uses established suppliers to cover the additional piece quantities.

Furthermore, if the quantity of parts is increasing it is possible to change to different manufacturing process.

Further emphasis on Standardization is also important in order to reduce internal variety.

Interim Evaluation of the design categories according to agility

Strengths:

-

Weaknesses:

The guidelines are too general and have to adapt to the specific area of usage.

Opportunities:

The applicability and the area of the agility guidelines have to be investigated. Where does it make sense to use modularity? Where is a variance of the modules useful?

Threads:

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Expert Interview with N.N (Anonymous)

Company Y, 11.3.2015

General Product Design Concepts

In general several design concepts are used within Company Y.
At first the approaches Design for Manufacturing and Assembly are implemented to ensure the manufacturability of the parts.
Furthermore, requirements engineering has the goal to forecast the product need for the next 5-10 years and to derive the product requirements. Quantity forecasts supports the requirements engineering to assess the right manufacturing process of the product.
The different variants of a new product are determined at the beginning of the development process, nevertheless the actual differentiation of the product should be in the production as late as possible (Delayed Product Differentiation).
Depending on the product quantity different effort of the development and design is done. For small quantities the design is focused on manufacturing processes within A, B and C samples. D-samples are allocated to the series production.
Furthermore, Front-Loading is split up into two main areas. At first, Front-Loading within the product development processes should reduce the development time due to the focus on simultaneous engineering. Another focus is on requirement engineering, which should be capable to recognise the customer wish. Within the location of N.N, it is focused on the second type of Front-Loading type.
The second Front-Loading is more future, overall oriented. Within this area, future technologies, within the manufacturing or software, are investigated. This is done within center of competence and all sites of Company Y are connected and have a cooperation with the centres. An Example of N.N was the manufacturing process autofrettage, which is investigated at the competence centre.

Agility and the derived Drivers

Agility is very important for Company Y in order to react to volatile markets.

In general the combination of the attributes functionality, reliability and costs are the basis for agility. N.N. emphasised that these three characteristics of a product have always to be fulfilled.
Furthermore, the importance of Costs are pointed out due to the fact that 70-80 percent of the products costs are determined during the product design.
Late Changes are not forced at the company unless the functionality is not satisfied and repair work has to be done. Late Changes is tried to avoid at any time.
Time to Market is very important to be faster in the development process.
Furthermore, Diversity of Variants ensures the easiness of deriving new variants from the existing modules.
Changes within the Quantity should be foreseen by the requirements engineering and are already implemented.

Product Design Concepts to increase Agility

Design for Switchability should ensure that minor changes within the material can be done. Nevertheless, the reliability of the product has always to be fulfilled.
For series production the design of the product is investigated after the SOP in order to reduce the manufacturing costs of the product. The changes should not weaken the reliability and functionality of the product. In the future, it should be focused to lower the rework and design the product already right at the first time.
Another concept to react agile is the platform approach. Within one product generation parts and modules are used to build up the platform for a product. Based on the platform, variant parts, which define the individual product, are designed. Special types, which requires special development effort, ensures that a broader portfolio can be handled. The product variants are already determined at the beginning of the concept phase.
The focus within Company Y for the next years is at two areas.
At first the basic modules and parts, which are be used in several parts should be more standardised. This should ensure that these parts can be used more often and the quantity is rising.
Secondly, the variant parts should be more broaden in order to offer more flexibility of the products. One example is a variant part, which should have

standardised clamps. Within the geometry different versions are possible nevertheless the clamps can be used for several variants.
Huge quantity changes can be covered due to the use of suppliers and with integrating other production sites of Company Y.

Interim Evaluation of the design categories according to agility

Strengths:
Very good approach to call attention to the possible influence of agility within the product design. It is both for managers and employees. The topic should be integrated in the EFQM Model at the enabler site within an organisation.
Weaknesses:
The catalogue is in common too general to use.
Opportunities:
The catalogue should be adopted to the different product and branches as well as to the size of a company (From a central, in depended location or in-house).
Threads:
None, unless the company is ignoring the importance of agility.

Expert Interview with Michael Wastian

Company Kristl, Seibt und Co. GmbH, 15.4.2015

General Product Design Concepts

Within Kristl, Seibt und Co. GmbH (KS) the design concepts Design for Assembly and Design for Manufacturing are used. These concepts should guarantee that the designed parts and assemblies can be produced easily.
Furthermore, the Design for Variety approach is used to derive new variants of products very easy. Mr. Wastian explained that one project consists of several sub-assemblies, therefore it is important to reuse these assemblies in an efficient way.
For expensive modules, the first draft of a design is investigated with design to costs guidelines. Mr. Wastian stated that with this approach costs can be reduced easily.
Special emphasis on modularisation helps KS to reduce the development effort. Mr. Wastian stated on the example air conditioner, which is used within several projects, that modularisation results to lower costs and higher efficiency.
Mr. Wastian explained on the example high dynamic frequency converter, that it is aimed to break down the complex design into modules. If a new test bench, in which the frequency converter is used, is built, a customized variant can be offered quickly.
Standardization should guarantee that carry over parts are used more often along the projects. An own developed software database delivers preferably parts to the design engineers.
Delayed Product Differentiation as well as Set Based Design is not used within KS. It is tried to focus on one solution as soon as possible.
Front-Loading supports the designer of KS during the whole development process. Simulations like Finite Elements Methods supports the engineers to design the product in an efficient way.

Agility and the derived Drivers

Agility is in general important for KS. Mr. Wastian explained that KS has a huge personal growth in the last years and faces an unknown future.

For KS, Late Changes are a normal topic as customers have during the product development process permanent design changes. Therefore, late changes are the most important agility driver.
Furthermore, the driver Diversity of Variants is important as KS provides individual solution.
Mr. Wastian stated that Time to Market means for KS to deliver the project right in time, which is necessary to satisfy the customers.
Quantity is not important as the batch size of the products are mostly 1.

Product Design Concepts to increase Agility

Mr. Wastian explained that for some clients, which are already known due to prior projects, special design measures are already considered prior. Higher end parts, which are usually not necessary, are used, to be able to compensate later product changes.
Within KS, further emphasis to improve the agility is done with the concept Design for Variety. Standardization and Modularisation approaches should support this demand.
In the future, it will be more focused on Front-Loading to reduce the development time. Furthermore, the design should be optimized with this approach.
Lastly, Design for Assembly and Manufacturing should always support the production.

Interim Evaluation of the design categories according to agility

Strengths:
The catalogue is a good general overview of guidelines. The pre-ranking already emphasis on the important concepts
Weaknesses:
-
Opportunities:
Who is responsible to implement the guidelines? Additional column, with more specific design examples.
Threads:
-

Appendix C Case Study Evaluation

Quantity (VENTREX)

	Qualitative Design Guidelines	General Categories	Internal Rating	VENTREX	Difference	Absolut	Number >1
1	Use standard components	Standardization	1.15	1	0.15	0.15	0
2	Use catalog parts	Standardization	1.25	0	1.25	1.25	1
3	Decompose cost-intensive components with a huge amount of variants to standard and variant components	Standardization	0.55	1	-0.45	0.45	0
4	Use of proven components, specify quality parts from reliable sources	Standardization	0.00	1	-1.00	1.00	0
5	Design parts to be multi-useable	Standardization	0.00	1	-1.00	1.00	0
6	Standardise design parameter (geometry, material ...) of different variants (e.g. raidius/depth ratio of a drilling hole)	Standardization	0.00	-1	1.00	1.00	0
7	Use overdesign to avoid product variants (e.g. make filling tanks larger than necessary)	Standardization	0.10	-1	1.10	1.10	1
8	Avoid right/left parts, Use Paired parts for twice the quantity and half the number of parts	Standardization	1.05	1	0.05	0.05	0
9	Maximize part symmetry e.g. square part, drilling holes with same distances from each other	Standardization	0.45	1	-0.55	0.55	0
10	Minimize the number of parts	Standardization	0.95	1	-0.05	0.05	0
11	Minimize the needs for special tools	Standardization	1.05	-1	2.05	2.05	1
12	Minimize Setups to reduce the production start time	Standardization	1.00	1	0.00	0.00	0
13	Minimize Cutting Tools for machined produced parts, minimize cost by designing parts to be machined with the minimum number of cutting tools	Standardization	0.70	0	0.70	0.70	0
14	Minimize costs related to Drawings and Documentation, e.g digitalization, use of CAD	Standardization	0.10	0	0.10	0.10	0
15	Minimize the number of assembly movements	Standardization	0.85	0	0.85	0.85	0
16	Minimize the number of assembly directions	Standardization	0.75	2	-1.25	1.25	1
17	Avoid separate fasteners, reduce the number of Bolts, or replace bolts by a snap lock	Standardization	0.95	0	0.95	0.95	0
18	Develop a modular design (for products where modules make sense)	Modularity	1.25	2	-0.75	0.75	0
19	Design module interfaces compatible	Modularity	0.20	1	-0.80	0.80	0
20	Assign every function directly to one module of the product	Modularity	0.10	0	0.10	0.10	0
21	Assign every variant product characteristic directly to one module	Modularity	0.20	0	0.20	0.20	0
22	Variant characteristics without any effect on the function should be isolated in new cost-efficient components (e.g. cell phone color)	Modularity	0.10	-1	1.10	1.10	1
23	Changing one product characteristic should not effect more than one module	Modularity	0.00	0	0.00	0.00	0
24	Use parallel and serial configurations to create perfomance variants (e.g. battery configuration, parallel to increase current, serial to increase voltage)	Modularity	0.10	-1	1.10	1.10	1
25	Use cut to fit modularity to create geometric variants (e.g. size variant of a role)	Modularity	0.00	0	0.00	0.00	0
26	Use additional elements to create geometric variants (e.g. size variant of a role)	Modularity	0.10	-1	1.10	1.10	1
27	Integrate one component with another so that: difficult handling is avoided, critical positioning or inlaying is avoided and the total number of operations is reduced	Modularity	0.85	1	-0.15	0.15	0
28	Several methods to develop a robust and error free product and to develop the right product. Quality function deployment (QFD), Failure modes and effect analysis (FMEA), Taguchi methods, Problem-solving techniques	General Guidelines	0.50	2	-1.50	1.50	1
29	Optimize Toleranzes and Surfaces, like as approximate as possible and as exact as necessary	General Guidelines	0.00	2	-2.00	2.00	1
30	Use software instead of hardware solutions to create product variants	General Guidelines	0.20	-1	1.20	1.20	1

Quantity (VENTREX)

	Qualitative Design Guidelines	General Categories	Internal Rating	VENTREX	Difference	Absolut	Number >1
31	Understand manufacturing problems/issues of current/past products	General Guidelines	0.10	1	-0.90	0.90	0
32	Develop new product variants based on a non-order-related variant	General Guidelines	0.00	1	-1.00	1.00	0
33	Product variety should be created in the end of the assembly process	General Guidelines	0.10	0	0.10	0.10	0
34	Raw material selection; Select a material which is easy available and avoid rare materials. Use material, which is easy to operate with machines	General Guidelines	1.65	1	0.65	0.65	0
35	Process selection; Define manufacturing processes, which are appropriate for the quantity and the existing product design, e.g. Welding vs. Casting vs. Bolts etc.	General Guidelines	1.25	2	-0.75	0.75	0
36	Adhere to specific process design such as welding, casting, forging, etc. E.g. For casting avoid cavities, provide radii, etc.	General Guidelines	0.65	0	0.65	0.65	0
37	Design for fixturing	General Guidelines	0.25	0	0.25	0.25	0
38	Provide simple handling and transportation	Handling Guidelines	1.05	1	0.05	0.05	0
39	If part symmetry is not possible, make parts very asymmetrical and provide orienting features to avoid assembly error	Handling Guidelines	0.65	0	0.65	0.65	0
40	Provide easy access for locating surfaces, symmetrical parts or exaggerate asymmetry	Handling Guidelines	0.35	0	0.35	0.35	0
41	Insert new parts into assembly from above	Handling Guidelines	0.70	0	0.70	0.70	0
42	Provide suitable lead-in chamfers for easier assembly	Handling Guidelines	0.75	1	-0.25	0.25	0
43	Provide alignment features	Handling Guidelines	0.75	2	-1.25	1.25	1
44	Design open enclosures	Handling Guidelines	0.55	0	0.55	0.55	0
45	Design parts so that they are easily oriented	Handling Guidelines	0.75	1	-0.25	0.25	0
46	Distinguish different parts that are shaped similarly thorough no geometric means	Handling Guidelines	0.45	1	-0.55	0.55	0
47	Avoid visual obstructions	Handling Guidelines	0.75	0	0.75	0.75	0
48	Avoid simultaneous fitting operations	Handling Guidelines	0.75	0	0.75	0.75	0
49	Avoid parts which will tangle or nest	Handling Guidelines	0.75	0	0.75	0.75	0
50	Avoid adjustments which affect prior adjustments	Handling Guidelines	0.85	1	-0.15	0.15	0
51	Avoid the possibility of assembly errors including Poka-Yoka Techniques	Handling Guidelines	1.05	2	-0.95	0.95	0
52	Place fasteners from obstructions, fasteners should be easily accessible	Handling Guidelines	0.55	1	-0.45	0.45	0
53	Provide flats for uniform fastening and fastening ease	Handling Guidelines	0.75	0	0.75	0.75	0
54	Proper spacing ensures allowance for a fastening tool	Handling Guidelines	0.65	0	0.65	0.65	0
55	Guide pins shall be provided for alignment of modules or high-density connectors	Handling Guidelines	0.85	0	0.85	0.85	0
56	Design for automatic assembly in order to achive uniform assemblies, few erroneous assemblies, uniform high quality and great system reliability	Handling Guidelines	0.85	-1	1.85	1.85	1
57	Manual assembly offers great flexibility towards: various product types, component variantions, faulty components, unforeseen assembly problems	Handling Guidelines	0.65	1	-0.35	0.35	0
58	Components should be able to withstand high-speed mechanical handling	Handling Guidelines	0.75	1	-0.25	0.25	0
59	Components should be free from oil or swarf	Handling Guidelines	0.25	2	-1.75	1.75	1
60	Use 'magazines', a mechanical form or frame which parts or wholly maintains the components in a constant orientation	Handling Guidelines	0.65	0	0.65	0.65	0
						SUM	13

Late Changes (KS)

	Qualitative Design Guidelines	General Categories	Internal Rating	KS	Difference	Absolut	Number >1
1	Use standard components	Standardization	1.25	2	-0.75	0.75	0
2	Use catalog parts	Standardization	0.95	2	-1.05	1.05	1
3	Decompose cost-intensive components with a huge amount of variants to standard and variant components	Standardization	1.35	2	-0.65	0.65	0
4	Use of proven components, specify quality parts from reliable sources	Standardization	0.00	2	-2.00	2.00	1
5	Design parts to be multi-useable	Standardization	0.55	2	-1.45	1.45	1
6	Standardise design parameter (geometry, material ...) of different variants (e.g. raidius/depth ratio of a drilling hole)	Standardization	0.25	1	-0.75	0.75	0
7	Use overdesign to avoid product variants (e.g. make filling tanks larger than necessary)	Standardization	0.95	2	-1.05	1.05	1
8	Avoid right/left parts, Use Paired parts for twice the quantity and half the number of parts	Standardization	0.55	2	-1.45	1.45	1
9	Maximize part symmetry e.g. square part, drilling holes with same distances from each other	Standardization	0.05	2	-1.95	1.95	1
10	Minimize the number of parts	Standardization	-0.35	2	-2.35	2.35	1
11	Minimize the needs for special tools	Standardization	0.10	2	-1.90	1.90	1
12	Minimize Setups to reduce the production start time	Standardization	0.00	0	0.00	0.00	0
13	Minimize Cutting Tools for machined produced parts, minimize cost by designing parts to be machined with the minimum number of cutting tools	Standardization	-0.10	0	-0.10	0.10	0
14	Minimize costs related to Drawings and Documentation, e.g digitalization, use of CAD	Standardization	0.00	2	-2.00	2.00	1
15	Minimize the number of assembly movements	Standardization	0.00	0	0.00	0.00	0
16	Minimize the number of assembly directions	Standardization	0.00	0	0.00	0.00	0
17	Avoid separate fasteners, reduce the number of Bolts, or replace bolts by a snap lock	Standardization	0.00	1	-1.00	1.00	0
18	Develop a modular design (for products where modules make sense)	Modularity	0.15	2	-1.85	1.85	1
19	Design module interfaces compatible	Modularity	1.15	1	0.15	0.15	0
20	Assign every function directly to one module of the product	Modularity	0.95	1	-0.05	0.05	0
21	Assign every variant product characteristic directly to one module	Modularity	0.85	0	0.85	0.85	0
22	Variant characteristics without any effect on the function should be isolated in new cost-efficient components (e.g. cell phone color)	Modularity	0.10	0	0.10	0.10	0
23	Changing one product characteristic should not effect more than one module	Modularity	1.25	1	0.25	0.25	0
24	Use parallel and serial configurations to create perfomance variants (e.g. battery configuration, parallel to increase current, serial to increase voltage)	Modularity	0.10	1	-0.90	0.90	0
25	Use cut to fit modularity to create geometric variants (e.g. size variant of a role)	Modularity	0.65	1	-0.35	0.35	0
26	Use additional elements to create geometric variants (e.g. size variant of a role)	Modularity	0.95	2	-1.05	1.05	1
27	Integrate one component with another so that: difficult handling is avoided, critical positioning or inlaying is avoided and the total number of operations is reduced	Modularity	0.00	2	-2.00	2.00	1
28	Several methods to develop a robust and error free product and to develop the right product. Quality function deployment (QFD), Failure modes and effect analysis (FMEA), Taguchi methods, Problem-solving techniques	General Guidelines	0.10	2	-1.90	1.90	1
29	Optimize Toleranzes and Surfaces, like as approximate as possible and as exact as necessary	General Guidelines	0.00	2	-2.00	2.00	1
30	Use software instead of hardware solutions to create product variants	General Guidelines	1.65	2	-0.35	0.35	0

Late Changes (KS)

	Qualitative Design Guidelines	General Categories	Internal Rating	KS	Difference	Absolut	Number >1
31	Understand manufacturing problems/issues of current/past products	General Guidelines	0.00	2	-2.00	2.00	1
32	Develop new product variants based on a non-order-related variant	General Guidelines	0.10	0	0.10	0.10	0
33	Product variety should be created in the end of the assembly process	General Guidelines	0.55	0	0.55	0.55	0
34	Raw material selection; Select a material which is easy available and avoid rare materials. Use material, which is easy to operate with machines	General Guidelines	0.00	2	-2.00	2.00	1
35	Process selection; Define manufacturing processes, which are appropriate for the quantity and the existingproduct design, e.g. Welding vs. Casting vs. Bolts etc.	General Guidelines	0.00	1	-1.00	1.00	0
36	Adhere to specific process design such as welding, casting, forging, etc. E.g. For casting avoid cavities, provide radii, etc.	General Guidelines	0.00	2	-2.00	2.00	1
37	Design for fixturing	General Guidelines	0.00	1	-1.00	1.00	0
38	Provide simple handling and transportation	Handling Guidelines	0.00	2	-2.00	2.00	1
39	If part symmetry is not possible, make parts very asymmetrical and provide orienting features to avoid assembly error	Handling Guidelines	0.00	2	-2.00	2.00	1
40	Provide easy access for locating surfaces, symmetrical parts or exaggerate asymmetry	Handling Guidelines	0.00	1	-1.00	1.00	0
41	Insert new parts into assembly from above	Handling Guidelines	0.00	1	-1.00	1.00	0
42	Provide suitable lead-in chamfers for easier assembly	Handling Guidelines	0.00	1	-1.00	1.00	0
43	Provide alignment features	Handling Guidelines	0.00	2	-2.00	2.00	1
44	Design open enclosures	Handling Guidelines	0.00	1	-1.00	1.00	0
45	Design parts so that they are easily oriented	Handling Guidelines	0.00	2	-2.00	2.00	1
46	Distinguish different parts that are shaped similarly thorough no geometric means	Handling Guidelines	0.00	1	-1.00	1.00	0
47	Avoid visual obstructions	Handling Guidelines	0.00	1	-1.00	1.00	0
48	Avoid simultaneous fitting operations	Handling Guidelines	0.00	1	-1.00	1.00	0
49	Avoid parts which will tangle or nest	Handling Guidelines	0.00	1	-1.00	1.00	0
50	Avoid adjustments which affect prior adjustments	Handling Guidelines	0.00	1	-1.00	1.00	0
51	Avoid the possibility of assembly errors including Poka-Yoka Techniques	Handling Guidelines	0.00	0	0.00	0.00	0
52	Place fasteners from obstructions, fasteners should be easily accessible	Handling Guidelines	0.00	2	-2.00	2.00	1
53	Provide flats for uniform fastening and fastening ease	Handling Guidelines	0.00	2	-2.00	2.00	1
54	Proper spacing ensures allowance for a fastening tool	Handling Guidelines	0.00	2	-2.00	2.00	1
55	Guide pins shall be provided for alignment of modules or high-density connectors	Handling Guidelines	0.00	2	-2.00	2.00	1
56	Design for automatic assembly in order to achive uniform assemblies, few erroneous assemblies, uniform high quality and great system reliability	Handling Guidelines	0.00	0	0.00	0.00	0
57	Manual assembly offers great flexibility towards: various product types, component variantions, faulty components, unforeseen assembly problems	Handling Guidelines	0.75	2	-1.25	1.25	1
58	Components should be able to withstand high-speed mechanical handling	Handling Guidelines	0.00	0	0.00	0.00	0
59	Components should be free from oil or swarf	Handling Guidelines	0.00	1	-1.00	1.00	0
60	Use 'magazines', a mechanical form or frame which parts or wholly maintains the components in a constant orientation	Handling Guidelines	0.00	1	-1.00	1.00	0
						SUM	26

Diversity of Variants (KNAPP)

	Qualitative Design Guidelines	General Categories	Internal Rating	Knapp	Difference	Absolut	Number >1
1	Use standard components	Standardization	0.75	2	-1.25	1.25	1
2	Use catalog parts	Standardization	0.45	2	-1.55	1.55	1
3	Decompose cost-intensive components with a huge amount of variants to standard and variant components	Standardization	0.75	2	-1.25	1.25	1
4	Use of proven components, specify quality parts from reliable sources	Standardization	0.00	2	-2.00	2.00	1
5	Design parts to be multi-useable	Standardization	1.15	2	-0.85	0.85	0
6	Standardise design parameter (geometry, material ...) of different variants (e.g. raidius/depth ratio of a drilling hole)	Standardization	0.65	2	-1.35	1.35	1
7	Use overdesign to avoid product variants (e.g. make filling tanks larger than necessary)	Standardization	0.35	2	-1.65	1.65	1
8	Avoid right/left parts, Use Paired parts for twice the quantity and half the number of parts	Standardization	0.17	2	-1.83	1.83	1
9	Maximize part symmetry e.g. square part, drilling holes with same distances from each other	Standardization	0.15	2	-1.85	1.85	1
10	Minimize the number of parts	Standardization	0.35	2	-1.65	1.65	1
11	Minimize the needs for special tools	Standardization	0.00	2	-2.00	2.00	1
12	Minimize Setups to reduce the production start time	Standardization	0.55	2	-1.45	1.45	1
13	Minimize Cutting Tools for machined produced parts, minimize cost by designing parts to be machined with the minimum number of cutting tools	Standardization	-0.10	2	-2.10	2.10	1
14	Minimize costs related to Drawings and Documentation, e.g digitalization, use of CAD	Standardization	0.00	2	-2.00	2.00	1
15	Minimize the number of assembly movements	Standardization	0.00	2	-2.00	2.00	1
16	Minimize the number of assembly directions	Standardization	0.00	2	-2.00	2.00	1
17	Avoid separate fasteners, reduce the number of Bolts, or replace bolts by a snap lock	Standardization	-0.10	2	-2.10	2.10	1
18	Develop a modular design (for products where modules make sense)	Modularity	0.85	2	-1.15	1.15	1
19	Design module interfaces compatible	Modularity	1.15	2	-0.85	0.85	0
20	Assign every function directly to one module of the product	Modularity	0.85	0	0.85	0.85	0
21	Assign every variant product characteristic directly to one module	Modularity	0.85	1	-0.15	0.15	0
22	Variant characteristics without any effect on the function should be isolated in new cost-efficient components (e.g. cell phone color)	Modularity	0.95	1	-0.05	0.05	0
23	Changing one product characteristic should not effect more than one module	Modularity	0.75	2	-1.25	1.25	1
24	Use parallel and serial configurations to create perfomance variants (e.g. battery configuration, parallel to increase current, serial to increase voltage)	Modularity	1.15	1	0.15	0.15	0
25	Use cut to fit modularity to create geometric variants (e.g. size variant of a role)	Modularity	0.10	1	-0.90	0.90	0
26	Use additional elements to create geometric variants (e.g. size variant of a role)	Modularity	0.65	1	-0.35	0.35	0
27	Integrate one component with another so that: difficult handling is avoided, critical positioning or inlaying is avoided and the total number of operations is reduced	Modularity	0.00	2	-2.00	2.00	1
28	Several methods to develop a robust and error free product and to develop the right product. Quality function deployment (QFD), Failure modes and effect analysis (FMEA), Taguchi methods, Problem-solving techniques	General Guidelines	0.00	2	-2.00	2.00	1
29	Optimize Toleranzes and Surfaces, like as approximate as possible and as exact as necessary	General Guidelines	0.00	2	-2.00	2.00	1
30	Use software instead of hardware solutions to create product variants	General Guidelines	1.35	2	-0.65	0.65	0

Diversity of Variants (KNAPP)

	Qualitative Design Guidelines	General Categories	Internal Rating	Knapp	Difference	Absolut	Number >1
31	Understand manufacturing problems/issues of current/past products	General Guidelines	0.00	2	-2.00	2.00	1
32	Develop new product variants based on a non-order-related variant	General Guidelines	1.35	1	0.35	0.35	0
33	Product variety should be created in the end of the assembly process	General Guidelines	0.35	1	-0.65	0.65	0
34	Raw material selection; Select a material which is easy available and avoid rare materials. Use material, which is easy to operate with machines	General Guidelines	0.00	2	-2.00	2.00	1
35	Process selection; Define manufacturing processes, which are appropriate for the quantity and the existingproduct design, e.g. Welding vs. Casting vs. Bolts etc.	General Guidelines	0.00	2	-2.00	2.00	1
36	Adhere to specific process design such as welding, casting, forging, etc. E.g. For casting avoid cavities, provide radii, etc.	General Guidelines	0.00	2	-2.00	2.00	1
37	Design for fixturing	General Guidelines	0.00	1	-1.00	1.00	0
38	Provide simple handling and transportation	Handling Guidelines	0.00	2	-2.00	2.00	1
39	If part symmetry is not possible, make parts very asymmetrical and provide orienting features to avoid assembly error	Handling Guidelines	0.00	2	-2.00	2.00	1
40	Provide easy access for locating surfaces, symmetrical parts or exaggerate asymmetry	Handling Guidelines	0.00	2	-2.00	2.00	1
41	Insert new parts into assembly from above	Handling Guidelines	0.00	1	-1.00	1.00	0
42	Provide suitable lead-in chamfers for easier assembly	Handling Guidelines	0.00	1	-1.00	1.00	0
43	Provide alignment features	Handling Guidelines	0.00	1	-1.00	1.00	0
44	Design open enclosures	Handling Guidelines	0.00	2	-2.00	2.00	1
45	Design parts so that they are easily oriented	Handling Guidelines	0.00	2	-2.00	2.00	1
46	Distinguish different parts that are shaped similarly thorough no geometric means	Handling Guidelines	0.00	1	-1.00	1.00	0
47	Avoid visual obstructions	Handling Guidelines	0.00	2	-2.00	2.00	1
48	Avoid simultaneous fitting operations	Handling Guidelines	0.00	1	-1.00	1.00	0
49	Avoid parts which will tangle or nest	Handling Guidelines	0.00	2	-2.00	2.00	1
50	Avoid adjustments which affect prior adjustments	Handling Guidelines	0.00	2	-2.00	2.00	1
51	Avoid the possibility of assembly errors including Poka-Yoka Techniques	Handling Guidelines	0.00	0	0.00	0.00	0
52	Place fasteners from obstructions, fasteners should be easily accessible	Handling Guidelines	0.00	1	-1.00	1.00	0
53	Provide flats for uniform fastening and fastening ease	Handling Guidelines	0.00	1	-1.00	1.00	0
54	Proper spacing ensures allowance for a fastening tool	Handling Guidelines	0.00	2	-2.00	2.00	1
55	Guide pins shall be provided for alignment of modules or high-density connectors	Handling Guidelines	0.00	1	-1.00	1.00	0
56	Design for automatic assembly in order to achive uniform assemblies, few erroneous assemblies, uniform high quality and great system reliability	Handling Guidelines	0.00	2	-2.00	2.00	1
57	Manual assembly offers great flexibility towards: various product types, component variantions, faulty components, unforeseen assembly problems	Handling Guidelines	1.05	1	0.05	0.05	0
58	Components should be able to withstand high-speed mechanical handling	Handling Guidelines	0.00	1	-1.00	1.00	0
59	Components should be free from oil or swarf	Handling Guidelines	0.00	2	-2.00	2.00	1
60	Use 'magazines', a mechanical form or frame which parts or wholly maintains the components in a constant orientation	Handling Guidelines	0.00	2	-2.00	2.00	1
						SUM	37