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# PRODUCT ROBUSTNESS AS A BASIS FOR THE IMPROVEMENT OF PRODUCTION PLANNING PROCESSES – KEY FACTORS IN EARLY DESIGN PHASES

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## ABSTRACT

Given the growing change of market conditions worldwide production planning is facing new challenges. Different conditions in terms of operating resources, knowledge and quality ask for more flexible processes. As a consequence these new circumstances have to be taken increasingly into account in early phases of product design. To support the adjustment between product and production development the most significant key factors in design concerning production processes must be identified. Therefore criteria are derived that describe the suitability of a product design to the production and the required quality – a measure to be introduced as product robustness. The methodical analysis of technical parameters of various product concepts, depending on their abstraction level and their interaction with each other, will support the generation of a guideline that indicates important effects certain design decisions have on the early production planning. Finally the measure product robustness can act as a basis for comparisons with measures like costs to support companies´ design decisions worldwide.

*Keywords: Product Robustness, Design for Manufacturing and Assembly, Flexible Manufacturing, Design parameters*

## 1 INTRODUCTION

In times of globalization customer markets are changing faster than ever before - companies are facing the challenge of responding to global customer requirements. Product requirements and structures become more complex while customer expectations increase at the same time. Products are not only sold all over the world but also manufactured worldwide. As a consequence the product development has to consider, besides new requirements and product design methods, also the global production processes of a certain company. To guarantee competitive results product development has to involve the production engineering as early as possible. A fact that several approaches of Design for Manufacturing (DFM)/ Design for Assembly (DFA) propose, e.g. [11], [13]. What is needed is a validation of the suitability of certain product concepts to the corresponding production. This is what in the following is considered as the robustness of products and product concepts. It is assumed that robust products can deal more easily than others with unsteady production conditions, e.g. oscillating quantities or different climates at different plants. Handling robust products is of special interest when customer requirements are changing and thus new product design alternatives must be generated. Starting with the actual state of a company´s production resources it has to be decided whether the existing plants are able to produce the new product or whether new lines have to be installed. On the other side at a certain break-even point even new technologies must be installed.

## 2 STATE-OF-THE-ART

### 2.1 Approaches of product robustness in technical fields

Several approaches in literature deal with the terms ‘robust’, ‘robustness’ or relating terms. For most authors robustness is the ability to deal with disturbances without lacking functional requirements [1], [2]. Taguchi et al.[1] claim that even deviances in between tolerance ranges can harm the final performance and small deviations of a target value are to be considered as a ‘quality loss’. Important parameters are therefore to be optimized in a way that the final product is not affected at all. As a consequence robust design asks for tolerances that are fixed more strictly the more impact the according deviation has on the functional performance of the system.

In addition a deeper look on the mentioned disturbances is needed. Regius [3] e.g. assumes that for a ‘robust construction’ all parts are manufactured in their required tolerances, but nevertheless failures occur, inside the system as well as in the working surrounding. Responsible are five categories of disturbing factors - part-to-part variance, wear over time, customer use, environmental influences and system interactions. Through a ‘robust matrix’ it is possible to state the most influencing factors.

Following Will et.al.[4] robustness is not a customer requirement. It is rather an important criterion that leads to requirements such as functional capability, functional safety and reliability. In the context of this paper, based on approaches of DFM/A, product robustness is not intended to characterise the final use of a product but more to characterise the ability of product concepts to handle changing production requirements.

Closely related to this context are considerations of robust processes. VDA [5] states robust processes as a company´s basis to assure market leadership in combination with a reduction of quality costs. Important factors are complexity and innovation, the human factor (lacking experience, failure to comply specifications, etc), the availability of resources (money, operating tools, etc), planned and unplanned changes in the production process (due to changes of customer requirements). As influencing factors with regard to the complexity and innovation the aspects high product variance and maturation are stated as influencing. Also the resistance against disturbances is mentioned as well as a production according to specifications at a required time without failures. The aim is to achieve the required product quality, that are in this context functions, defined characteristics, application and durability. But also this approach leaves out the way production has an impact on a concrete design concept.

In the context of robustness also the term flexibility is to be considered. In the field of manufacturing system design (MSD) flexibility is defined as the ability of the development process to adapt to changed conditions, such as resources and requirements [6]. Relating is the term mutability of production systems. According to Nyhius et.al.[7] the system is then able to react in case of changes, e.g. of running quantities, when so called mutability enablers like universality (to design and to dimension the system that it can react to changing requirements, e.g. well trained workers that can handle several processes), mobility (objects like tooling can be moved to arrange the layout on demand), scalability (changes of technical, spatial and personal capacities), modularity (ability of a production system to use modular tooling) and compatibility (e.g. controlling several machines with one software) are given. According to Saitou et.al.[8] robustness of flexible manufacturing systems (FMS) exists if the production is highly efficient without lots of system reconfigurations even when production plans are changing in a certain (predicted) range.

### 2.2 Planning of production processes

According to DIN 8580 [9] manufacturing processes in general can be devided into six main groups that are casting, forming, joining, cutting as well as coating and changing the material characteristics. These groups again can be subdivided in more than one hundred subgroups to which about 50 norms refer to. In addition also assembly, logistics and quality control have to be considered for an integral planning [10]. Degarmo et.al.[11] define a manufacturing system as ‘the complex arrangement of the manufacturing elements (physical elements) characterized (and controlled) by measurable parameters’. Physical elements include machine tools for processing, any tooling, material handling equipment and people. To assess the performance of the process measurable parameters as throughput time and daily or weekly volume can be used.

Furthermore production planning has to consider requirements of the manufacturing and assembly like flexibility and mutability as mentioned in Section 2.1. Production quantity and product variety influence each other – high production quantity matches most likely with a low product variety. Variety in the context of production engineering indicates different shapes and sizes that meet different functions. So a product designed for mass production will show up a different construction as one for a job-shop [12], [13]. Thus the required quantity gives first hints for the product design. At a certain break-even point technology jumps might be necessary due to strict tolerances – meaning special tools, special knowledge and experience as well as strict conditions to the environmental surrounding as temperature and humidity.

Nevertheless today´s production planning is a field of such complexity that product development can not consider all necessary aspects during the design process. In companies mostly only the problem causing parameters are known for standard processes of that particular company but not for new or furthermore outsourced technologies. Not stated are limits for the different production technologies from the product designer´s point of view, e.g. to which extent tolerances can already be predicted when deciding to cut a single part instead of casting it.

### 2.3 Product design in early phases with emphasis on production aspects

Product development processes in general are well described, e.g. in VDI 2221 [14] and VDI 2222 [12]. They propose different abstraction levels to run through in order to generate consistent product concepts. Starting with customer requirements functional structures and working principles are generated, followed by the conceptual design of parts and products [10]. The more concrete the design the more technical parameters are fixed. According to VDI 2221[14] on the level of principle solutions first geometries due to a certain effect as well as the motion and the type of material are set. Dependent on the innovation grade it has to be assessed to which extent some parameters in general are changeable.

Some literature mentions the necessity of product design to answer to production challenges, see Design for manufacturing and assembly (DFM/A), e.g. [11], [13]. Since production processes have to be as economic as possible some basic rules can be formulated. Thus product design has to be simple in terms of geometry and surfaces, to avoid unnecessary strict tolerances and finishing requirements in order to avoid further processes. Standard materials and common components are to be used as well as standardized design for similar products. A minimization of the number of components can be achieved by integral architectures [13], [15]. In order to facilitate the process of finding common elements classification and coding systems are implemented which use several design and manufacturing parameters. In Table 1 a propose after Lal et.al.[15] is given that mentions parameters such as major dimensions, tolerances, material type and part function as important. Missing is an indicator for their impact and the design phase in which they have to be fixed. Also Downey et. al.[2] ask for an early control of key characteristics, defining them as parameters that refer to features of the product and variables of the manufacturing as well as the assembly process, since they are the most sensitive ones to variation and indicate the product performance the most. In general factors that influence the production itself are rarely indicated. The incorrect design of fixtures, possibly caused by a lack of skills and experience on workers side, tool wear in general and environmental effects lead to products of low quality in the end [16].

*Table 1: Design and manufacturing attributes [15]*

| Design Attributes | Manufacturing Attributes |
|---|---|
| Basic external shape | Major process |
| Basic internal shape | Operation sequence |
| Major dimensions | Batch size |
| Tolerances | Machine tool |
| Surface finish | Cutting tools |
| Part function | Annual production |
| Material type | Major dimensions |
| Length to diameter ration | Length to diameter ratio |
| | Basic external shape |
| | Material type |
| | Tolerances |
| | Surface finish |

According to Degarmo et.al.[11] at least up to the functional level of product design engineers mostly ignore whether a certain product configuration can be produced economically with the available resources. And even in that situation only the knowledge about feasible processes is not sufficient. Also limitations and costs are to be considered. Material is stated to be one of several obvious determinations by product design whereas tolerances are to be called indirect what leads to closer tolerances than necessary as seen above. Fallböhmer [17] defines an optimal adjustment between material, form and technology as follows. After defining the functional relevant characteristics of a material a certain material family has to be found that leads, after certain geometrical definitions, to possible production technologies. Afterwards more restrictions show up the necessary material what defines again the final geometry.

Some literature proposes methods to ease manufacturability, see e.g. [10] and [15]. In the following just three examples are given: 1) concerning casting rounded corners are favoured to permit a uniform cooling, 2) in the field of machining sequences of operations are to be kept in mind and the surface to be machined should be as small as possible, 3) drilling tools should be arranged orthographically to the parts face in order to guarantee a straight run. Nevertheless all these examples refer to very concrete and final concepts and might not give the necessary hints in early phases.

# 3 DESIGN TO ROBUSTNESS

## 3.1 Criteria for product robustness

Taking into account the information and specifications of product as well as production design (see Section 2) certain criteria can be stated as important for product robustness. Product robustness includes therefore a mixture of both product and production engineering. The earlier manufacturing designers know about key characteristics of the design like geometry or tolerances the earlier they can start with planning the layout. Necessary and possible operating resources can already be estimated to a certain extent. This can save money since investments are negotiated with more calmness. In addition the layout can be planned more flexible if product design leaves some degrees of freedom – e.g. if production sequences do not matter (e.g. the processes 'drilling' and 'joining' of a part then can easily be changed in their sequence). Since product designers always try to define close restrictions to guarantee customer´s requirements most design concepts are full of very strict and mostly complicated geometries as well as close tolerances. It has to be checked whether several design points can be changed without any disadvantage for the customer. Either some restrictions can be avoided to ease the production planning worldwide or at least in early discussions some unchangeable parameters can be stated to those the manufacturing and assembling processes must be adjusted.

The choice of material also affects the choice of certain tools. It has to be examined whether e.g. a physical effect answering a certain function can be realized differently in order to facilitate the production layout. This could also affect the environment since restrictions such as vacuum production might not be necessary. Concerning the mentioned customer requirements it has to be made clear which decisions in product design are connected to which customer requirements. The ones with a high priority are supposed to have more impact on the production design and finally on the production costs. Furthermore it is imaginable that instead of performing to a strict required value, e.g. the velocity, certain ranges can be achieved including the actual requirement. In this way the product design does not need to be changed enormously. Even when requirements are changing in future the implemented lines can deal with these new challenges. Figure 1 shows in summary the most important criteria.

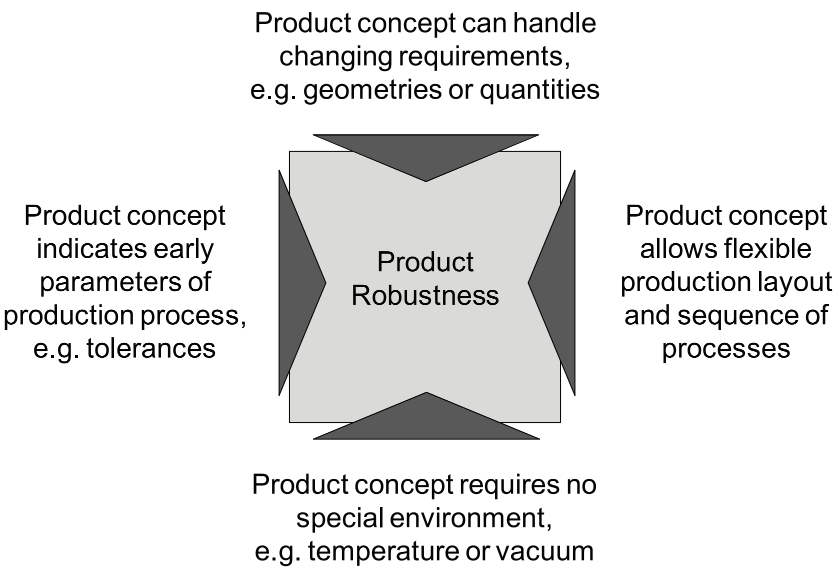


*Figure 1: Main criteria for product robustness*

As mentioned in Section 2 (see [4]) the term product robustness in this context is to differentiate clearly from quality parameters like reliability, safety or aspects related to the customer use. All these aspects will be taken into account since they are included in the customer specifications. In other words a robust product answers to reliability and safety requirements, and tries to find the most suitable way in production to meet these requirements.

### 3.2 Methodical approach and important aspects

Starting with the criteria shown above that are to be considered to evaluate the product robustness, in the following it will be pointed out how important parameters will be identified in order to lead to a generic guideline. The continuous analysis of abstraction levels paves the way to a generic validation of the product robustness in different industries and for different products.

The project going along with this analysis gives the opportunity to have insights in different industries and products. Different project partners support the specification of all necessary steps - from the product characterisation to the validation of possible alternatives. At the beginning all necessary technical data is taken down for the reference products. Therefore the actual state is described through requirement lists, functional modelling, sketches of concepts and all necessary data about the final construction – for both product and production.

Afterwards all this information has to be assigned to certain abstraction levels, see Figure 2 on the left side. It is supposed that most of the data are to find on the more concrete levels, e.g. parameters like geometrical constraints and relating tolerances. But because of certain physical and chemical effects the product is based on material and dimensions that were already decided some time before – functional requirements might have been realised by other physical effects. It will be shown which decisions are made automatically in early stages. Complex structures can be avoided by using other physical effects that facilitate manufacture and assembly design. It will be of great interest how long degrees of freedom exist for different product fields. Moreover it has to be examined which parameters on a concrete level are interacting with parameters on lower levels and how many restrictions on a level $a_1$ lead to (more numerous) interacting restrictions on level $a_2$, see Figure 3. So to say the decision to use an aluminium alloy as material depends on the decision to go for a metallic material. This again is based on the decision to use magnetism as effect and this again is required by the function `to hold (s.th.)`. At the same time aluminium as a material requests certain tolerances that can be predicted much earlier. This interaction among the levels has to be shown up in order to generate independent conclusion about product robustness.

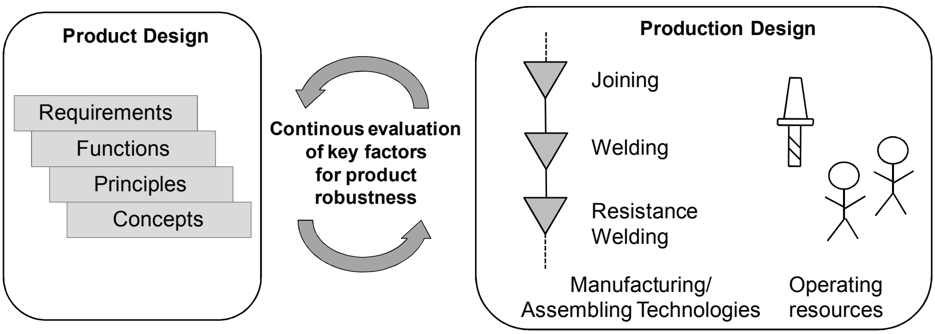


*Figure 2: Continuous adjustment between product and production design*

Mentioned on the right side of Figure 2 the planned manufacturing and assembly steps for the reference products are taken down. Already in this phase alternative layouts or tools are listed together with possible problematic points. Based on DIN 8580 [9] also the production technologies and processes will be assessed on different abstraction levels. So for a metallic material e.g. first geometries already indicate cutting as a process, but the specific cutting process for aluminium is predictable later on. Aspects concerning the operating resources like processes, tools and grade of automation are put into a scheme. The discussion about alternative scenarios between product and production development will assign the most influencing design parameters and the challenges of production.

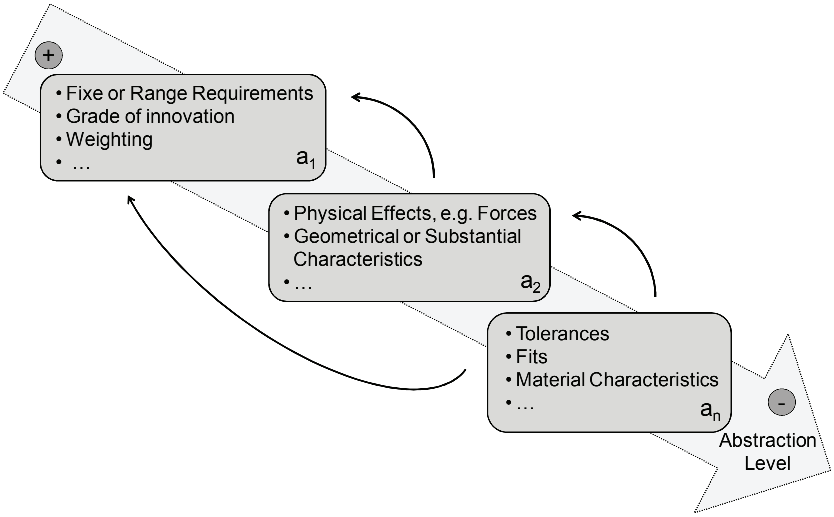


*Figure 3: Influencing parameters on different abstraction levels*

When all available and derived parameters are structured on several abstraction levels it has to be examined in what manner the technical parameters of one abstraction level are interacting with each other. Thus three different aspects will be mainly examined – complexity, conflicts of objectives as well as variants or similarity, see Figure 4.

Complexity:
First of all the analysis of complexity as a key factor for product robustness will focus on product complexity. Product complexity is characterised by elements and their interactions with each other, considering also dynamic changes. Mainly nature and number of all three aspects are examined [18]. Taking the example of tolerances it will be shown how many different tolerances of a product are related to each other and with what impact. Moreover a used material like aluminium in the final design and its highest temperature in use are closely connected to the required tolerances. Besides it must be analysed to what extent also complexity in production is of importance to evaluate product robustness. Possibly the analysis of interactions in production technologies and processes on different levels, starting with the machines in general and ending with a certain velocity of a drilling tool, will lead to significant conclusions.

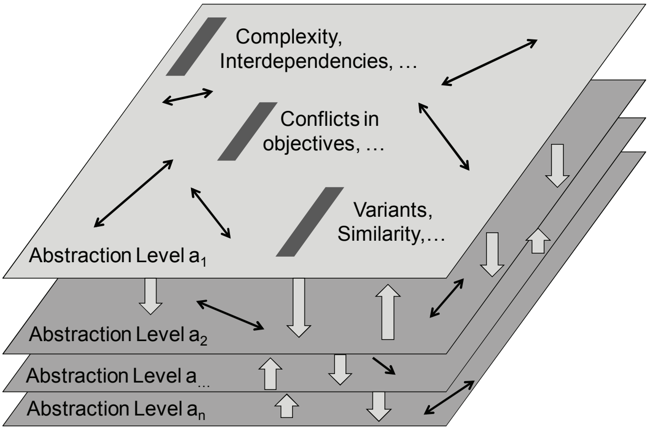


*Figure 4: Interaction between influencing parameters on a single abstraction level*

Conflicts in objectives:
At the same time the analysis of conflicts on different abstraction levels is examined. Conflicts are both effects of certain technical parameters of the product as well as their relation to production parameters. May be that a product concept in a certain phase asks for two types of machines that can not be integrated in the layout due to differences in sequences. Possibly also conflicting requirements are based on conflicts in the production. If the output of a certain machine is not high enough one with a higher one might be chosen, even if that means a smaller selection of materials.

Similarity:
In addition to the examination of the variability of product elements it is important to see which conclusions can be derived from information about product similarity. It is assumed that in case of similar structures more information about standard processes of former products is available and thus the production planning is more easily to handle. It will lead to a conclusion to which extent one production facility (line, job-shop etc) can handle variants. Referring to Ehrlenspiel et.al. [19], who propose several parameters that can be changed in product design, reference products will be analysed. Besides number (i.e. related to one geometrical characteristic), material and size also the connection type (e.g. welding or bonding) and the type of contact (e.g. as a point or a line) are mentioned, among others. To evaluate differences in certain concepts Heß [20] suggests an analysis through distance vectors or matrixes. Since meeting customer requirements is the key factor for success also they will be compared to each other to indicate whether different concepts are most likely of the same structure if referring to similar requirements.

### 3.3 Evaluation of product robustness

After taking down all necessary data of the reference products and showing up all significant connections between the parameters it must be evaluated at what point a product can be called robust in the context of this paper and with which impact the above shown criteria describe robustness. In the following a choice of the expected results is pointed out.

Regarding the amount of data and parameters that will come out of the analysis it is supposed that less restrictions lead to product robustness. E.g. a design characterized by lots of tolerances challenges the production more than one with only little. The same applies for environmental conditions. Furthermore the quality of interactions between the single abstraction levels is of importance. The best, in terms of product robustness, e.g. one parameter on abstraction level $a_2$ belongs to one on the higher level $a_1$ or at least certain parameters on $a_2$ can be related clearly to one on level $a_1$ – a classical hierarchical structure. If parameters on all levels are related crosswise the design will get less robust.

This applies also to a single abstraction level. Complex interactions of the parameters with each other lead to little clusters and the final design gets more complex itself. Also a low level of conflicts supports a robust design. The more similar two designs are the more information and knowledge of a former product can be applied. That is why this criterion is favoured very high. The analysis of the reference products will show which aspect is more influencing, e.g. the geometrical or the technological similarity.

Since the producibility is closely connected to the term product robustness in the context of this paper relating aspects will influence the evaluation as well. The more different technologies and sequences are imaginable for a certain product the more robust it is. In case only one single machine in the company can handle the necessary process already small interruptions of the production will cause great problems. So to say the number of manageable variants will be significant. Moreover concepts that can be manufactured and finished with technologies already implemented and therefore experienced in a company will lead to more robust results. In case new technologies can not be avoided either their number or their similarity to known processes will indicate the robustness.

## 4 CONCLUSION

The derived criteria to assess product robustness focus on structuring design parameters on different abstraction levels, taking into account the restrictions production planning is facing at the same time. For several reference products alternatives in product and production design are examined in order to line out the most important key factors in form of a guideline that will facilitate processes of design to manufacturing and assembly in early design phases, probably customized for a single company.

Through the examination of products of different branches of industry it will be shown whether the assessed key factors are varying. So the comparison of mechanical and mechatronic products will likely point out diverse design decisions at the time. Geometrical aspects might be more important for the first group whereas mechatronic products focus on decisions concerning the electronic part and thus more complex environmental conditions.

To complete the evaluation also the availability of technical information in a company has to be considered in future - in which form and to what extent. Aspects of design processes such as time and the impact of decisions will complete the evaluation. Especially the examined key factors must be considered by all departments that are involved in the whole design process.

In a first step the product robustness is practicable for a certain company to get an idea of its own ‘relative’ product robustness. Updates of a design or changing requirements of a single product will be assessable with this methodology. So to say the focus is on internal validations between product design and production planning, at a maximum for products of the same business unit. In a further step it possibly can be used to compare products of the same industry field.

Concerning a certain coefficient to state the product robustness it has first to be validated in what way this measure can be evaluated mathematically through numbers and quotients. Of course tools like the analysis of matrixes, i.e. the cluster analysis, will lead to certain coefficients. But since the product robustness is meant to drive the discussion between different departments instead of delivering complicate mathematical calculations an applicable method is to be implemented. Most likely considerations such like spin nets or portfolio analysis will lead to better conclusions.

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