INTERNATIONAL DESIGN CONFERENCE - DESIGN 2010
Dubrovnik - Croatia, May 17 - 20, 2010.

DESIGN 2010

A PROCEDURAL MODEL TO ASSESS MAIN INFLUENCES OF PRODUCTION ON PRODUCT DESIGN

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Keywords: product robustness analysis, design for manufacturing and assembly, multiple-domain matrices (MDM)

1. Introduction

In times of an increasing cost and competitive pressure, companies need to adjust their internal processes earlier in order to be economically successful. Production as one of the important limiting aspects needs to be considered as early as possible. Especially since the number of variants increases, and requires more flexibility of internal processes. The communication gets even more difficult, if product development and production planning are not in the same place. In most cases only the company´s main implemented production processes as well as related challenges are known to the product designers. Therefore the two areas design and production need to be coordinated in very early phases and to be leveled through a common understanding and common models.

In the ongoing project we therefore analyze the possibility to integrate generically production aspects into the design process in very early phases. Therefore both the product development as well as the production planning process is analyzed for all participating companies. Furthermore several approaches for modeling such concepts are conducted. Finally robustness is examined for the product concept as well as for a production system. In this paper we will focus on product robustness. In short, this term describes the suitability of a product concept for production. We finally strive to generate a guideline that covers overall general key factors and gives instructions for the product design. The corresponding procedural model for the research within the project is shown to give an overview. In contrast to traditional approaches of Design for Manufacturing and Assembly (DFM/A), these instructions are supposed to be on the one hand more specific in order to be applied in industry. On the other hand they need to be abstract enough to allow within the companies a transfer to other products than the ones examined within the project.

In the field of product development a lot of procedures and models are implemented, but less in production planning. To analyze the most important interdependencies of design decisions we propose the analysis of both the product and the production resources on different abstraction levels in order to identify the most significant influences. The examination through a Multiple-Domain Matrix (MDM) helps to determine both interdependencies within product and production concepts and the concept spanning ones between the different areas. Since robust product concepts are flexible towards changing production conditions we especially examine the influence different production alternatives have in order to identify the key factors for the design of robust products.

2. Product design and modeling of production processes – State of the art

2.1 Product Robustness

According to most references in literature that deal with „robust“ and „robust design“, these terms describe the ability to deal with disturbances without lacking functional requirements [Taguchi et al. 2005]. Taguchi et al. concentrate on the optimization of technical parameters, mainly tolerances, since even slight deviations of a target value influence the final product performance. To further elaborate this “insensitiveness” to variations some more aspects are considered for the ongoing research. As Helten et al. [Helten et al. 2009] state a robust product concept can easily deal with changing customer requirements. At the best the production layout has not to be changed enormously. Furthermore it is the goal to generate product concepts that can be handled by the most possible production facilities and process technologies. The sequence of the processes should not matter and no special tooling should be necessary. This aspect includes knowledge as well. In addition product robustness requires that environmental circumstances do not harm the result such as for example production under vacuum does. So to say a product concept is robust in this context, if it can be produced under changing production conditions [Helten et al. 2009].

2.2 Modeling of production processes

In general production processes can be ordered hierarchically as stated in DIN 8580 [DIN 2003]. Beginning from a general division into main groups like casting and joining, the processes can be assigned to more than one hundred sub-groups that again refer to more than 50 technical norms. Swift and Booker [Swift and Booker 2003] offer so called PRIMAs (Process Information Maps) that enable designers to get an overview of the most important information about material suitability, special design considerations and process fundamentals. According to Groover [Groover 2002] certain constraints are to be respected. Some basic processes lead to certain secondary processes, as well as property-enhancing and finishing operations. If the product is sand casted, machining follows as secondary process. In general many aspects are to be considered for production related design decisions. Aspects regarding the process and sequence, tools and equipment lead to more criteria. The processes should ensure net shapes and flexibility towards design changes [Groover 2002]. Swift and Booker [Swift and Booker 2003] state material to be the ruling aspect. Missing in literature is any advice of how to avoid such a limiting factor and in which phase of the product design process. Designers need to know about the influences the product has on the production design and vice versa.

Of course factors such as production quantity and product variety are of great importance when planning the production process but are not in the focus of this paper. Here we will concentrate on theoretically possible production alternatives in order to analyze interdependencies in general. All aspects related to an optimization and economic planning will be addressed from other academic partners within the project.

Both for a first draft of a process as well as for a detailed analysis Brandis et al. [Brandis et al. 2009] introduce a holistic approach to model the production system and to show the interactions with the product concept. The approach consists of four partial models: manufacturing requirements, process sequence, resources, and shape. Especially the model of the resources includes information about the necessary semi-finished parts and manufacturing functions/processes.

2.3 Models for product development

Most literature about product design proposes hierarchical approaches. Even if they differ in number and meaning of certain levels, most approaches start with an analysis of customer requirements and get more specific during the process [e.g. Pahl et al. 2007, Ponn and Lindemann 2007]. The modeling of the functional structure leads to physical effects and finally to concepts. Consequently the number of fixed technical parameters increases over time. For the further analysis in this paper we will, referring to Ponn and Lindemann [Ponn and Lindemann 2007], use and adapt four abstraction levels: Model of requirements, Model of functions, Model of working elements, and Model of components. Section 3.3 shows an example.

Generally there are several approaches to integrate aspects from other areas and departments into the design process. Such strategies are Integrated Product Development, Simultaneous Engineering, and Concurrent Engineering. Design for Manufacturing and Assembly (DFM/A) is a further one with the focus on production aspects. Swift and Booker [Swift and Booker 2003] offer a list of general guidelines to ensure producibility. Thus e.g. the number of machined surfaces is to be minimized and secondary processes are to be avoided. On the other side Pahl et al. [Pahl et al. 2007] suggest some very concrete advices that are divided into the main process groups like welding and casting. Hence for example designers are supposed to plan rounded corners for casted parts to permit a constant cooling. In order to guarantee a straight run any drilling tool should be arranged orthogonally to the part´s surface. Swift and Booker [Swift and Booker 2003] underline the influence of parameters such as dimensions, tolerances, material and surface finish requirements. The PRIMAs they offer, see 2.2, indicate for example the appropriate surface roughness ranges and show the process capability chart with the correlation between dimension and tolerance.

Huang [Huang 1996] proposes a DFX shell that supports the design of any DFX tool. It includes seven steps that are iteratively connected. Based on an analysis of the requirements for such a tool and the important aspects to focus on, product and processes need to be modeled. Afterwards a suitable measure is generated to support the decision process and the evaluation of product concepts. Finally the implementation in industry is prepared through manuals and workbooks, before the implementation process gets verified.

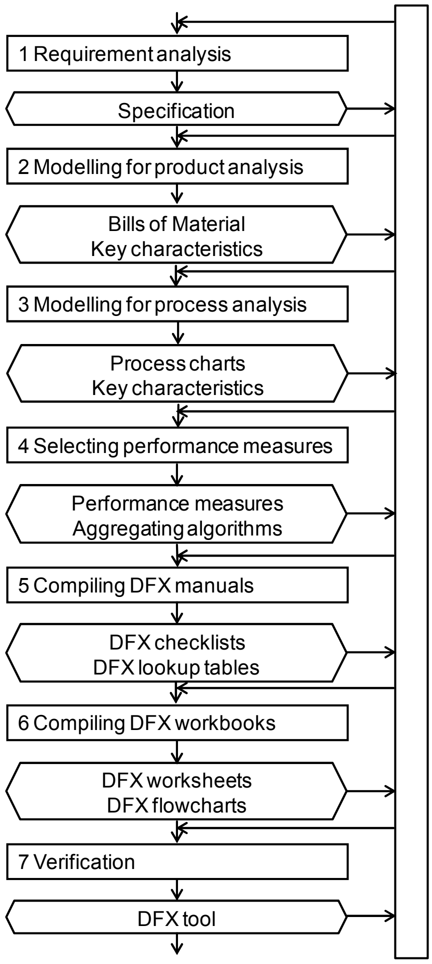

Figure 1. DFX shell for development of DFX tools [Huang 1996]

In summary the methods for an integration of production knowledge into the product design process are in general either too abstract or too concrete to be applied in early stages. On the one hand a general advice like the reduction of the number of parts does not ease the assembly in every case. On the other hand any concrete advices can only be applied, if the main design decisions concerning material and technological process are already made.

2.4 Analysis through Multiple-Domain Matrices (MDM)

Since a lot of information from two different disciplines has to be analyzed we propose the use of a matrix based method. As a combination of a Design Structure Matrix (DSM) and a Domain Mapping Matrix (DMM) the Multiple-Domain Matrix (MDM) allows the analysis of different system perspectives [Lindemann et al. 2009]. Hence it is possible to identify the interdependencies of different domains, i.e. for this context either of product and production system itself as of both areas in combination. Moreover several criteria can be applied in order to characterize the overall system. Mainly active (element with high influence on others) and passive sum (element strongly influenced by others), criticality (element either strongly influences main threads of a system or is highly influenced from others), and an influence portfolio (with axes "active sum" and "passive sum") are used. The elements of a structure can furthermore be characterized by the impact of their influence (Closeness), and whether they are isolated from the system (Isolated node) or the only connection between other elements or sub-systems (Bridge node) [Lindemann et al. 2009].
In the field of production planning matrices are used so far to find similarities in the product architecture with the aim to select certain resources and production technologies and to group them according to the architecture, like theories of Group Technology. But these approaches do not consider the operating resource as a product itself and thus on different abstraction levels. As proposed by Helten et al. [Helten et al. 2009] the comparison of both concepts will help to assess product robustness.

3. Methodological approach to assess product robustness

3.1 Procedural model for the research

Even if at the beginning of the project a concensus existed among the industrial partners about the need of a robustness analysis, all partners had different aspects to consider. The challenges varied from the number of units, thus the grade of automation, to the abstraction level of the considered product concepts. Therefore it was necessary to generate on the one hand a procedure that could be applied generically in all companies and allows the discussion of key factors. On the other hand it must also allow the measurement of a specific product robustness, see figure 2.
Based on the definition of robustness throughout the project, both the product concept as well as possible production processes are modeled with respect to different abstraction levels, see section 3.3. In the following the most influencing factors of production on the product design will be assessed, currently through a MDM. Especially the analysis of elements that change for different alternatives is of importance. Based on the MDM for each process concept, first key factors and interdependencies can be stated. Both steps, the modeling and a first analysis, are conducted for several components and process steps (see "Variations" in figure 2). In this manner the examined factors get approved for one company. After the analysis of significant domain and concept spanning interdependencies the findings are summarized to find first hints on product robustness. To confirm the significance of the examined factors, the procedure up to this point is also conducted for all companies separately (see the parallel charts in figure 2). By putting together overall specific factors a generic robustness measure is generated. In the last step we need to find overall influence threads and clusters that will facilitate the product design for new components. As described in 2.2, the aim is to generate a guideline that supports the companies in modeling as well as evaluating. Since industry can not assess robustness with so much time and effort the guideline will propose just a few models and measures that can be integrated in the actual processes of the companies. Therefore the last two (generic) steps are as often as possible compared to the preceded steps to evaluate their industrial feasibility and significance.
The procedure shows up a similar structure as the DFX shell, see figure 1. Beginning with the discussion about the focus and the requirements for the tool, both areas are modeled, a measure is generated, and documents are prepared for the implementation. In addition, the modeling phase in this project is broadened to different companies to get more feedback regarding the practicability. The

stepwise evaluation focuses on the modeling part. This enables us to understand the industrial need more clearly and to derivate as early as possible those kinds of models that can be used after the project in industry. In contrast to the DFX shell, we focus more on the interdependence analysis on different levels, and on the question, on which abstraction levels in the design process certain production aspects are implemented the best.

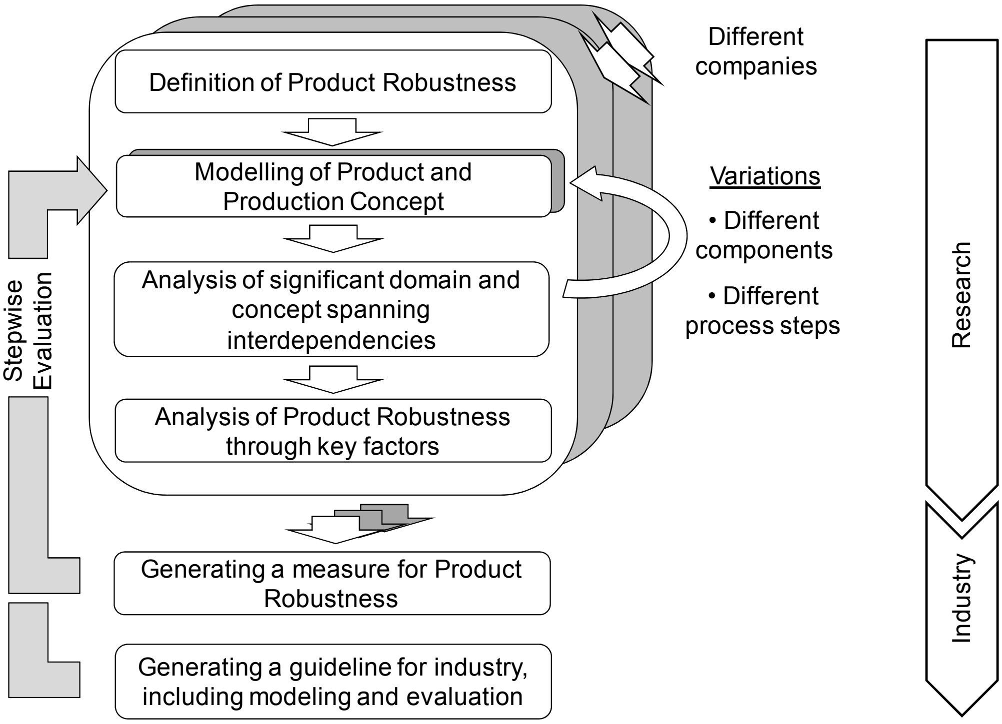

Figure 2. Procedural model to assess product robustness

3.2 Adaption of the procedural model to different companies

The procedural model of section 3.1 is adapted to the specific needs of the participating companies. The companies come from different areas (suppliers for automotive, banking and printing industry). They vary in the grade of automation of the production facilities, in the focus on production vs. assembly/ national vs. international facilities, and the degree of novelty. To some extent we are able to support the identification of critical process steps and monitor the design of new production resources. In addition different layouts of existing resources in a single company and their influence can be examined. Also interesting is the analysis to which extent production and assembly aspects are already included in actual product concepts.

3.3 Modeling product and production concepts on different abstraction levels

As proposed before, four abstraction levels are used to model both the product and the production concept. Figure 3 shows exemplarily how the requirements and parameters on different levels interact with each other. In order to show the evolution of the model, the figure still indicates similar levels for both areas, see Model of requirements etc. In the following sections the levels will be named slightly different. The required power for example leads to the function “To put pressure on” that again asks for a certain compressive force. The function “To direct a medium” bases on the requirement “flow rate” and correlates with the question how adhesion can be handled. On the level of working elements therefore both elements (force vs. adhesion) interact with each other and probably lead to a conflict of objectives. This conflict can be projected on the following level where the hardness interacts again with the material. The need for a bore is based on a function two levels earlier and requires any kind of drilling machine on production side. Moreover the product tolerance has influences on the precision of the tooling. The two functions on product side lead to two main production functions, “To bore” and “To harden”. In this case most likely the bore is done before the hardening. So there is a restriction for the sequence of processes. Tracking back the main correlations, the selection of a drilling tool is closely related to the requirement “Flow rate”. A change could be achieved for example on a higher level by using another principle than shearing strain for the hole.

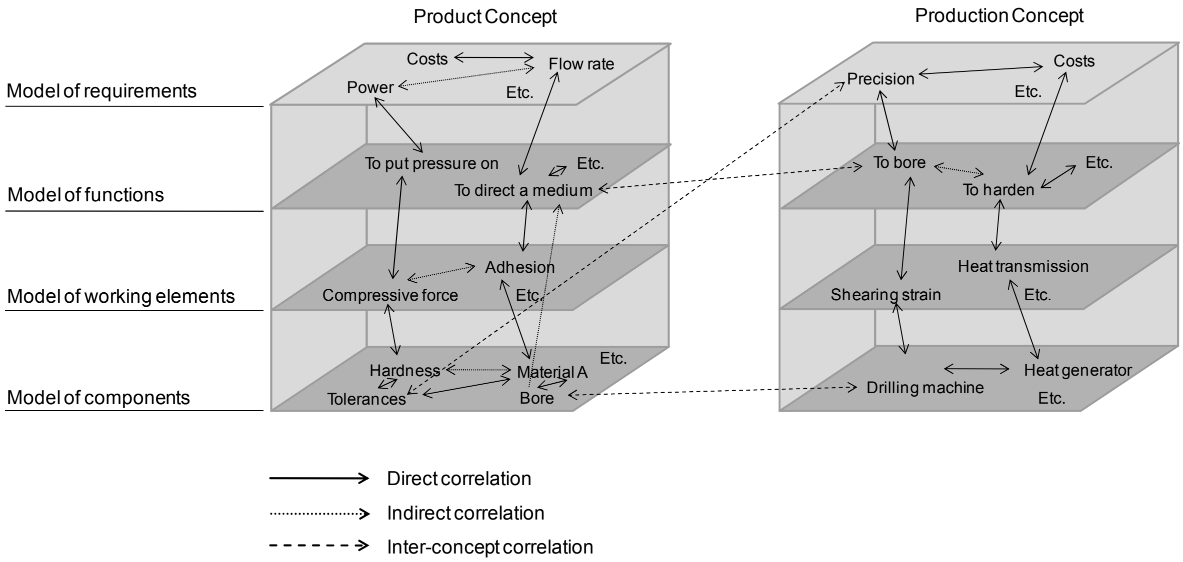

Figure 3. Concept analysis for product and production

3.4 Content and structure of the MDM

In the following the focus is on the interdependence analysis via MDM (see figure 2 “Analysis of Product and Production Concepts”). The overall MDM consists of eight domains - product and production system each of four (Product concept: Requirements, Functions, Principles, Components; Production Concept: Requirements, Process steps, Resources, Parameters). The matrix is directed. In figure 4 the upper left side shows the MDM of the product concept (M_1). For a single product only the actual state is analyzed. The lower right side shows the MDM of the production (M_2). Here the actual state as well as several alternatives is analyzed. The other two matrices represent the correlations of the coupling matrices (M_{12} and M_{21}). In the following, there is to differentiate between intra- and inter-domain matrices that refer to either the product or the production, and inter-concept matrices that bring together both points of view. The parallel charts represent the different production concepts that are examined.

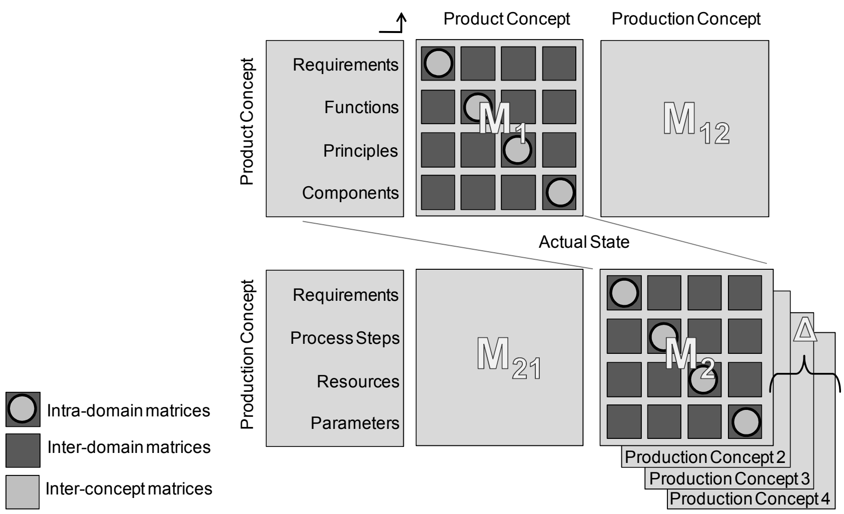

Figure 4. MDM for product and production concepts

For the research moreover several sub-matrices have been identified that are of major relevance for the robustness analysis, see marked sub-matrices in figure 4. For each sub-matrix the correlation is fixed, e.g. “interacts with”, “needs” and “fulfills”. For example product requirements INTERACT with each other, a product component REQUIRES a certain process step, and the process steps again REQUIRE several production resources. The matrix is fulfilled from the upper left to the lower right side. In order to assess the product robustness the significant interdependencies within the production sub-matrices need to be compared to the product architecture. Therefore in the matrices on the lower left side it is tested whether important parameters are met. For this transfer also the findings for the different alternatives (see Δ in figure 4) are of importance. For example it is analyzed whether certain elements replace others, or whether a single solution needs more elements. Also the analysis of constant elements throughout the alternatives is relevant.
So far this MDM is complete for one company and gets fulfilled by other companies at the moment. First hypothesis have been formulated with respect to product robustness. In addition to this kind of investigation, the sub-matrices are characterized by several measures, like activity and passivity, see section 2.4.

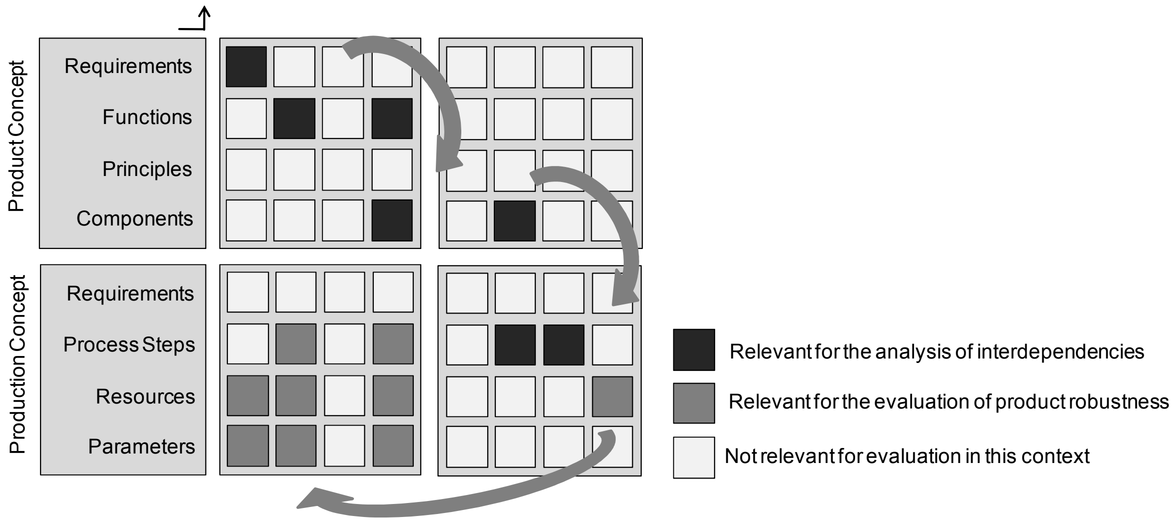

Figure 5. Relevant sub-matrices and correlations for the robustness analysis

4. First analysis of the interdependencies

4.1 First findings to improve the approach

So far we conducted the procedure till the analysis of main interdependencies for one of the partner companies. Through several workshops the MDM is completed according to figure 5. The findings can be divided with respect to their relevance for 1) the product matrix (M_1), 2) the process matrices (M_2) and 3) the coupling matrices (M_{12} and M_{21}).

Product matrix M_1

The analysis shows that especially on the functional level several product functions are modeled that are indeed important for the product performance, but are not related to any of the examined production steps. Therefore we have to minimize the number of elements after a first modeling and to define clearly the system boundary. If e.g. certain parts of a component will definitely not be changed for the next product generation, they should not be handled like an influencing factor on the production process. The same applies for other levels, especially the product requirements. At least the requirements must correlate with selected critical process steps and leave thus certain degrees of freedom to the design.

Production matrix M_2

Due to the early design phase the examined process alternatives are still on a very abstract level. During the analysis it becomes obvious that the alternatives are difficult to compare since they are partly referring to different aspects or vary in their abstraction level. This leads to two possible conclusions.

Even if the overall aim is a guideline for very early phases, there is a need to be more specific for the research. That does not mean to concretize the concept up to every single tolerance, but at least the completeness of an alternative must be guaranteed and principle chains must be considered. When considering an assembly step e.g. the contact between certain parts and the tool as well as the actuation of the tool itself must be taken into account. Otherwise it is not possible to model the difference between a manual and an automatic process properly and to compare differentiated mechanical/mechatronics solutions. Moreover experiments and tests can be planned more adequately based on the first brainstorming sessions. If not possible, at least a literature research must follow the first brainstorming sessions, and precede a further evaluation of any alternatives. At the moment several tests for the examined company are conducted that concretize the production requirements.

Mainly on the level of process steps either a more granular modeling must be implemented or the intra-domain correlations must be assigned with some strength or weight. The matrices show up hardly any difference between the production concept alternatives, e.g. when considering mechanical and mechatronics aspects. Since this finding can not be approved by the experts from industry we propose a more detailed evaluation of the correlations of the process steps.

On the level of resources and parameters, clear differences of production alternatives are shown. In order to analyze them properly the algebraic sign is taken into account when generating a delta matrix. This allows the analysis of whether certain elements of a concept 1 are only replacing others elements of another concept 2 or whether concept 1 consists of additional elements. To show whether in consequence an alternative creates more complexity in the system helps the measure of the product robustness.

Concept coupling matrices M_{12} and M_{21}

In a prior phase 32 sub-matrices (M_1 and M_2) were completely filled. For each of the eight domains approx. 10-20 elements were surveyed. This number was too high to examine for every single product. Therefore the most significant sub-matrices were identified as shown in figure 5.

In general the industrial partner evaluated the procedure as very useful. The need of filling the process matrices brought together experts from different departments. The different abstraction levels for the processes, even if still to improve, highlighted the challenges single departments are facing. Even among the production engineers information and knowledge is varying in its concreteness. The engineers share the opinion that due to this differentiated modeling many challenges that normally come up later in the production planning are addressed very early in this manner. The designers could systematically bring together their design parameters with production aspects. Therefore they underline the usefulness of analyzing the delta between the process alternatives.

4.2 Further investigations

The MDM has been introduced and discussed in all partner companies and got or gets filled through workshops with participants of both areas in near future. Even if still several points of the evaluation method need improvement, the main inter-domain matrices as well as inter-concept matrices show up main threads. Based on them several hypotheses are formulated that mostly refer to the indicated sub-matrices of figure 5. Exemplary calculations of characteristic values like the activity and criticality charts of the matrices underline the changing character of the production and its influence. Therefore it is planned to integrate these values into any form of measure for the robustness, for example a robustness profile.

The need for a further concretization of the concepts raises the question about what early design phases are. For most companies and sectors main gates are different. Depending on their market and portfolio they define different points for design freezes. It will be shown whether the specification of certain process points according to a certain type of company is useful. Nevertheless for the ongoing research for sure more concrete parameters are necessary to find main influences that can again be abstracted afterwards.

5. Conclusion

The procedure model including the modeling of product and production concepts on several abstraction levels allows companies a better understanding of the influence certain design parameters have on the production system. It enables them to design more robust products. This approach could also be used for other DFX challenges like services or environmental aspects.

Thanks to the initiating analysis in one of the partner companies the model in could be largely assessed for the first time and several points for further improvement could be specified. For instance the system´s boundary must be chosen properly. So far some parameters had a huge influence on the production, even if actually they are not to be changed for the next product generation. Furthermore the abstraction level of the production concept matrices need to be more specific, with the aim to evaluate their differences more in detail. Especially the difference of components or tools directly in contact with the product parts and the actuation of the tools is to be considered.

The overall structure of the guideline depends on future results. Probably the products themselves are divided into classes, e.g. mechanical vs. mechatronics, individual vs. mass products, or the production concepts are clustered according to the grade of automation. The term product robustness as introduced in this context is meant to support internal discussions and decisions. If customer requirements or production conditions change, the product design can integrate these changes faster than before. Even if the guideline and the corresponding measure are meant to be as generic as possible, it is not the aim to compare different products from different companies or sectors to each other through this measure.

The first analysis underlines similarities of important robustness indicators and characteristic criteria of a MDM analysis. First hypothesis are formulated that need verification. They mostly refer to number and character of the production alternatives (see lower right side in figure 3). Furthermore the degree of performance of the product specifications through the alternatives is mandatory. We intend to measure product robustness by kind of a profile. In that manner more different aspects can be assessed instead of calculating one single coefficient. In the near future the profile and the necessary measures are calculated and discussed with the companies to improve the validity if necessary.

Besides information about modeling and evaluating a guideline for industry needs to be embedded into the specific product development process. Therefore the development process of the different companies is analyzed to connect procedural steps as seen above and the necessary information with the current process.

Acknowledgement

This research is supported by the Bundesministerium für Bildung und Forschung (BMBF), Germany, through the project "VireS – Virtuelle Synchronisation von Produktentwicklung und Produktionssystementwicklung" (engl. Virtual Synchronisation of Product Development and Production System Planning").

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