



METHODICAL SUPPORT FOR CONCURRENT ENGINEERING ACROSS PRODUCT AND PRODUCTION (SYSTEM) DEVELOPMENT

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Abstract

Today, the implementation of concurrent engineering is further progressed on a strategic level than on operative level. Methods connecting both domains, product and production (system) development, are not yet advanced in order to fully exploit the potentials for cross-domain targets, e.g. minimization of the lifecycle energy consumption. This contribution describes a scientific formalization how product characteristics and production system characteristics depend on each other. Furthermore, a method that enables the multidimensional evaluation of product solutions with production system solutions is introduced in order to support decision making process in early product and production (system) development phases. The result of the method provides a combination of optimized solutions for product and production system.

Keywords: Concurrent engineering (CE), Integrated product development, Product and production (system) development

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Please cite this paper as:

Surnames, Initials: *Title of paper*. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. nn: Title of Volume, Milan, Italy, 27.-30.07.2015

1 INTRODUCTION

Targets like shorter product lifecycles, faster ramp-up times and the increasing number and complexity of product variants require a simultaneous development of products and the corresponding production systems. Thus, "concurrent engineering" is a term that has been stressed for a long time, already. In practice, however, its implementation is much further progressed on a strategic, often buzzword, level than on an operative level. Today, both domains - product and production (system) development - are often linked from an organizational perspective, only, what is not sufficient in order to meet the rising challenges. Design target such as, e. g., the minimization of the life cycle energy consumption require integrated cross-domain analysis and decision processes in order to exploit all possible potentials, as product-related and production-related decisions in both domains mutually influence each other. Thus there is a need for domain-spanning methods and processes in order to achieve best results for such targets. As a base for these methods, the interrelationships, how product characteristics and the characteristics of the corresponding production system depend on each other, have to be exploited and formalised.

Typically, there are discrepancies or even contradictions between methods from product development and production system development, or (partially) integrated methods often only use unidirectional linkages, such as DfX methods. In this area, research is necessary to unlock the potential of a deeper integration of both domains. Therefore, in this paper, existing methods are examined and modified or extended in order to model this correlation and assess the influence of inputs and results for development steps between product and production system development.

The use case for this research will be the optimizing of the lifecycle energy consumption. Energy efficiency of the whole lifecycle is a field of ever rising importance in engineering. The limited availability of non-renewable energy resources and the fact that renewable energy is not able to cover the overall energy consumption require a deeper consideration and improvement of the energy demand of the product lifecycle in order to face this situation. So far, energy optimisation in production is often only executed reactively; i. e. existing production systems are modified after startup to save energy. Potentials of such approaches are limited, as optimization options are limited. For comprehensive savings, energy consumption has to be addressed earlier in the product creation process, and integrated across product and production (system) development.

The structure of the paper is as follows. Section 2 gives an overview of state-of-the-art processes and methods in the domains of product development and production (system) development, respectively, as well as integrated approaches across both domains. In section 3, the need for action is worked out on the basis of a correlation matrix presented in previous work of the authors. Then, section 4 addresses this need by presenting a formalization of the correlation between product characteristics and production system characteristics. Afterwards, chapter 5 introduces an integrated method that targets the cross-domain evaluation of product and production system solutions. Finally the paper will be concluded and an outlook on further research will be given.

2 STATE-OF-THE-ART

In this section, general process models and methods in the domains of product development and production (system) development are introduced. Additionally, existing approaches that especially focus on the interaction between both fields are shown.

There are a lot of different methods and process models in the field of product development, following more or less similar steps. A well-recognized process model is, e. g., provided by the VDI guideline 2221 (VDI, 1993), beginning with a conceptual design phase over an embodiment design phase to a detailed design phase. Methods like requirement lists, morphological charts, Quality Function Deployment (QFD) or checklists are widespread to support selected steps of the process models. In contrast to classical (mainly mechanical) products, the VDI guideline 2206 (VDI, 2004) addresses the development of mechatronic products, presenting a V-model that contains a system design phase, domain specific design phase and a system integration phase. Both VDI guidelines' process models end up with the provision of manufacturing documents, a consideration of manufacturing processes as such is not focused on; it may only be performed in order to ensure special properties of some design elements (e.g. gliding surface). From a scientific perspective, Weber (2005) presents with the so-called CPM-approach a method that formalizes the relation between characteristics that can be directly affected and the resulting properties of a product.

In contrast to the well formalized product development, production (system) development is generally described in a rather abstract way. The VDI 4499 guideline (VDI, 2008) provides a rough process model for developing production systems, beginning with a planning step, over a domain specific development of mechanical and electrical components as well as control software to commissioning activities and finally the start-up of the production system. According to Belgran (1998), developing time is reduced when independent tasks are executed in parallel; furthermore, as several production system properties are already determined by product development, both processes should be parallelized in order to avoid time consuming iterations at the end. This postulation leads to the question how properties of product and production system depend on each other.

There are process models and methods that link product and production (system) development, but they often do not focus a fully integrated view.

Simultaneous and Concurrent Engineering as general philosophies have been stressed by engineering literature for a long time (e.g. Smith and Eppinger, 1998, Vajna et. al., 2005, Ehrlenspiel and Mehrkamm, 2013). Domains traditionally kept separate or even sequential from organizational, methods and tools perspectives have to be parallelized or front-loaded. Whereas needs for and benefits of such approaches are generally made very clear, concrete methodical support is often still lacking.

Whereas contemporary Concurrent Engineering approaches may even increase the overall workload (Smith and Eppinger, 1998), the presented integrated approach strives to reduce it, even if the workload in early phases may increase.

Design for Manufacturability (Molloy, 1998) or Design for Assembly (Andreasen, 1988), e. g., are strictly unidirectional, as they just incorporate manufacturing and assembly restrictions into product development. The similarly unidirectional Quality Function Deployment method developed by Akao (1990) is used to translate customer needs into characteristics of different abstraction levels. By a concatenation of several QFD steps (see figure 1), a step-by-step translation of the voice of the customer into product functions and principles solutions, process structures and the production technology definition can be derived. Through this method, a relation between design characteristics and manufacturing characteristics is established. In order to assess production system properties related to principle solutions, a possibility of feedback would however be necessary. For this reason, an extension of the QFD method that creates a reverse relation between the production system and product would be required.

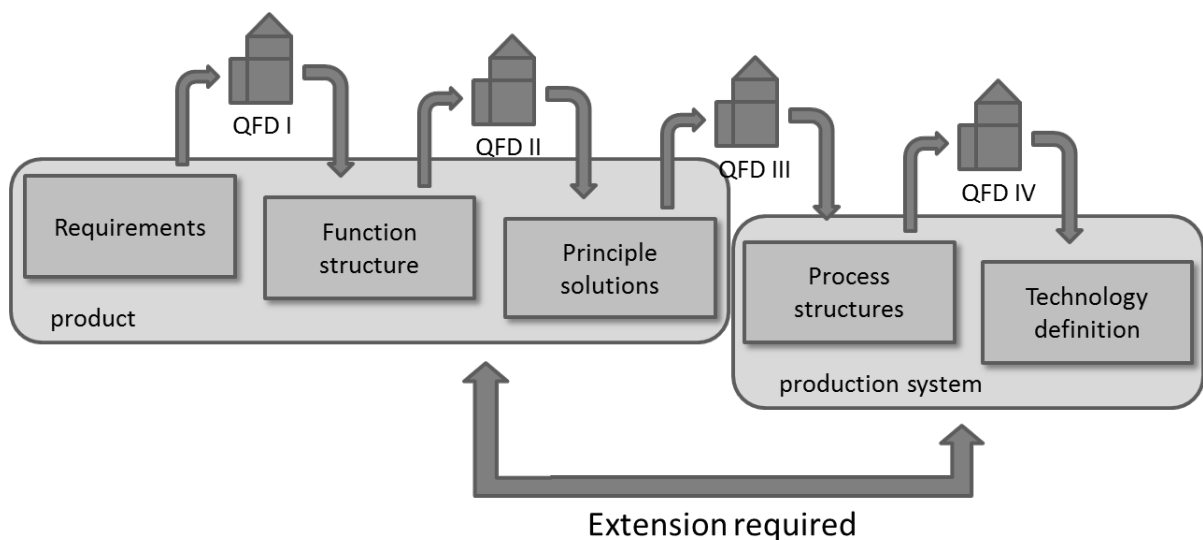


Figure 1. Deriving manufacturing characteristics from design characteristics by using QFD, based on Akao (1990)

On the example of robust products, Helten (2010) developed a procedure model that targets the visualization of the interdependencies between product and production concepts in order to help companies to understand the influence of design parameters on the production. Gausemeier (2010) proposes a specification technique for a domain-spanning description of the principle solutions of a product as well as the respective production system for mechatronic products. In this approach, the conceptual design of the production system is derived from the principle solution of the product.

As concurrent engineering, that actually targets the co-creation of products and the respective production system, is often implemented from an organizational perspective, only, methodical support is however lacking. Information is exchanged through common milestones and cross-domain team meetings, only. This situation leads to large and time-consuming iteration cycles and potentially suboptimal results concerning all aspects requiring a deeper integration, e. g. the energy consumption in production. The potential of getting more suitable product solutions concerning domain-spanning targets by using the correlation of both spheres is not considered, sufficiently. A method that correlates results of the process steps of both domains can be a powerful tool to achieve a more transparent evaluation and, finally, domain-spanning optimization.

3 NEED FOR ACTION

Section 3 discovers potential fields of action in order to integrate the spheres of product and production (system) development from a methodical perspective.

On an abstract level, products and production systems do not differ substantially from each other. Both domains' process models are based on similar steps and results (see figure 2), but the correlation between the results of different process steps of both spheres is normally neither regarded nor addressed. The connection between the two domains is normally conducted by requirements and assessments of the manufacturability of desired characteristics. The characteristics of the product are often untouchable from a production perspective, as long as they are manufacturable.

Changes to a product to allow for potentially more suitable production solutions are often neglected, because the technical function has utmost priority. Other constraints like costs may only increase, if at all, when they will be covered by resulting savings in production. A multidimensional evaluation method for different product solutions together with their production solutions can be an approach in order to create more efficient production systems.

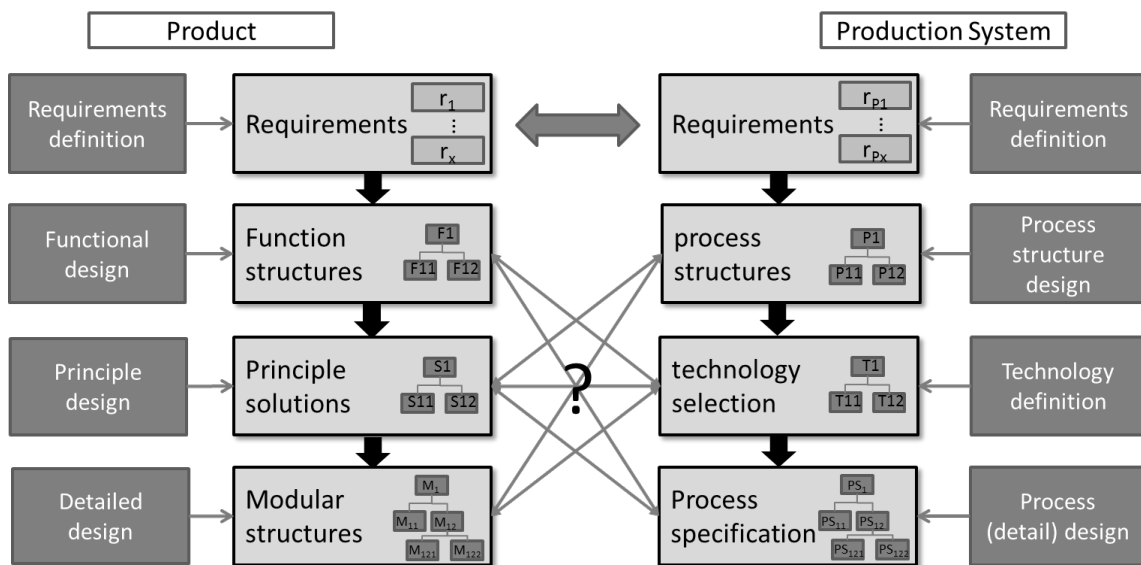


Figure 2. Mapping between phases and results in product and production system development

Optimizing the interaction between product and production (system) development first of all requires an analysis of the relations and interdependencies of both fields. In previous work of the authors an integration framework for product engineering and production engineering has been developed, providing an overall matrix that correlates phases from the product definition, the production definition and the material definition together with the input and output factors of the product creation process (Stoffels et al., 2014). This matrix allows evaluating the significance of the (directed) relations between these phases. It can thereby serve as a methodical basis for various use cases which depend on cross-domain relations and which require cross-domain decisions. For this work, material selection is not further considered and therefore omitted (see figure 3).

This correlation matrix has been filled with data from expert interviews (Stoffels et al., 2014). Strong relations have especially been identified between Principle Design (D2) and Detailed Design (D3) on

the product side and the technology definition (P1) and the Process design (P2) on the production side, notably in both directions, respectively. Depending on the scenario, different directions (and matrix areas, accordingly) may be predominant. In the case of new production systems the area bottom right is relevant and in the case using an existing one the top left is relevant.

As mentioned, the correlation of both domains is especially significant in the marked areas. Thus these relations are of outstanding importance for cross-domain engineering tasks such as the minimization of the lifecycle energy consumption, integrated tolerance management or cross-domain change management. In these areas, the interdependencies between decisions on concept or characteristic level within product and production (system) development are especially important to find overall optimized solutions. Thus in the following chapter, a formalization and methodical approach for these areas will be presented.

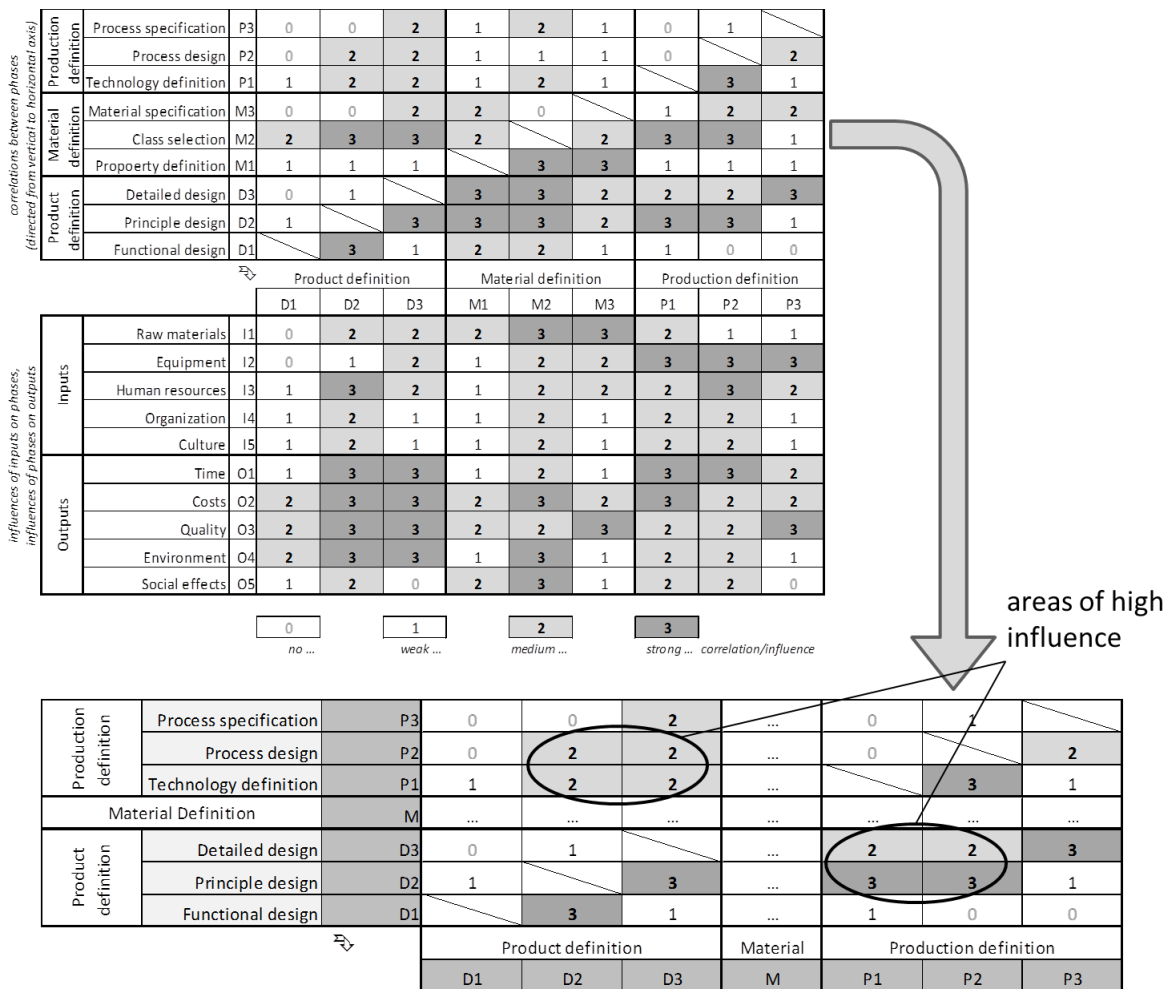


Figure 3. Excerpt from correlation matrix between product and production (system) development (Stoffels, 2014)

4 FORMALIZATION

As a basis for an integrated method development, a further formalization of the relationships between both domains' objects can be helpful. Therefore this section contains a formal description of how product properties and production system characteristics depend on each other. The CPM model of Weber (2005) will be taken as a basis for this formalization. The model describes the relation between (intended) product properties (P) and (designed) product characteristics (C). The properties result from the characteristics that are influenced by the engineer. A correlation matrix describes how both values depend on each other. R describes the correlation matrix for the analysis process, the inverse matrix for the synthesis process. An extension of this product-focussed model to also incorporate the corresponding production system is capable to describe the required dependencies between the product properties/characteristics and the production system. The production system itself can also be

described with the CPM model (Deubel, 2006), while $R_{ps,x}$ correlates the properties $P_{ps,x}$ and the characteristics $C_{ps,x}$. The product characteristics C_x are then determined by the properties of the production system $P_{ps,x}$. The correlation matrix $S_{p,ps,x}$ represents the linkage of both values in the analyses process. Similar to the origin CPM model, the inverse matrices can be used for the synthesis process, where PR is the required property.

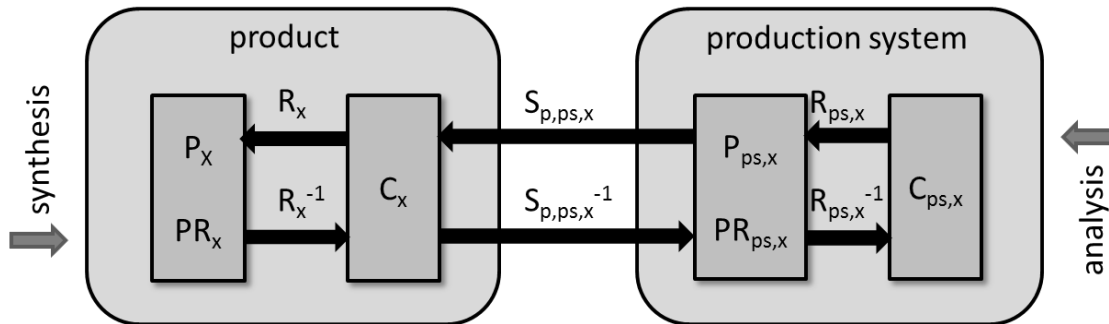


Figure 4. Synthesis outgoing from the required product properties to the characteristics of the production system based on Weber (2005) and Deubel (2006)

This theoretical description of the interdependencies between the product and the production system can be used for integrated assessments of different product solutions together with production solutions according to different criteria. Due to complex correlation matrices however, it may be difficult to use the detailed mathematical relation in the development process. Thus there is a need for simpler assessment methods that allow the developer to choose the best product solution and the corresponding most suitable production system, together. One such method is presented in the following section.

5 INTEGRATED MORPHOLOGICAL CHART METHOD

In this section, a method that targets the early assessment of principle product solutions together with corresponding possible production solutions is presented.

The classical morphological chart method provides a powerful assessment tool for decisions of conceptual product solutions in a very early development stage, see e.g. Pahl and Beitz (1988). The degree of freedom on design elements is still high in early stages of the process, why evolutionary solutions are achievable. In the further development process, the design gets more and more frozen, the freedom of action becomes smaller and changes can cause high efforts on products as well as the production system. For this reason it is very useful to position suitable methods in this area. By using morphological charts, different possible principle solutions for the required product functions are assessed according to different criteria, depending on the company. The fulfilment of the technical function is of primary importance, besides quality and costs. Nowadays, proven technologies are dominating this decision process. Alternative solution possibilities that result in more suitable production solutions are not considered enough.

The Integrated Morphological Chart as developed by the authors extends the classical morphological chart method by adding production solutions to the assessment system, first. The production system functions and the respective principle solutions have to match with the manufacturing of the principle solution of the product. The structure enables the assessment of a product solution and the corresponding production system solution in an integrated way. It thereby allows for integrated cross-domain decisions in order to find global (i. e. domain-spanning) optima rather than combining two domain-specific ones. It therefore adds a multidimensional evaluation matrix that links both domains morphological sub-charts. The principle solution $S_{x,y}$ for function F_x is assessed according to the energy consumption of different possible solutions ($SP_{n,m}$) for the functions of the production system FP_n .

An evaluation according only to one criterion such as the minimisation of the energy consumption in production is not sufficient enough to get more suitable solutions of both total systems. For this reason the evaluation and optimisation matrix is multidimensional regarding several criteria, for example technological, economical or ecological evaluation. The single results will be summarized and/or combined with a weighting of the criterion. The total result provides a combination of principle

solutions for the product and a combination of principle solutions for the production system that is most suitable considering the required criteria. The multidimensional evaluation is important not to optimize one criterion at the expense of another one.

The Integrated morphological chart enables an evaluation of abstract principle solutions for product functions as well as more detailed overall solution concepts and the corresponding production system regarding different criteria. In practice, due to the combination of solution principles from both domains and the incorporation of a multidimensional optimization, the integrated morphological chart may reach a size and level of complexity difficult to handle. Therefore, it's envisioned by the authors to develop a supporting IT-tool, accordingly.

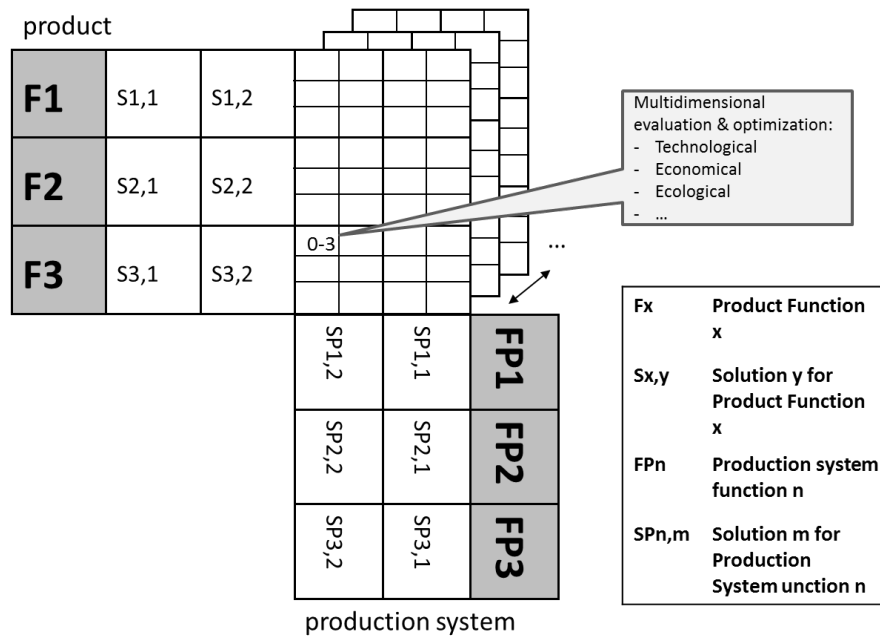


Figure 5. Multidimensional evaluation of product solutions according to their energy consumption, as well as other criteria in different production system solutions

The described method is able to deeper connect the domains of product development and production (system) development by supporting cross-domain development decisions. The deeper integration enables a common view on both systems and results in more suitable solutions relating to the entire product creation process. Furthermore, the method provides an overall structure for product and production solutions. From an organisational perspective, all persons that are involved in one of the evaluation criteria have to get access for assessing the matrix. The weighting of different criteria depends on the philosophy of the company. In order to get product characteristics that consume less energy to get manufactured, quality or technical functionality is untouchable, but for example increasing manufacturing costs could be accepted, if energy savings are realised.

6 CONCLUSION

Targets like the minimization of the lifecycle energy consumption suffer from a more or less isolated consideration and development of products and the corresponding manufacturing system concerning design characteristics. Product solutions are selected according to values like costs and quality and of course functionality. Solutions that match in the best way are taken, other solutions that do also well are rejected even if they would apply on constraints of another organizational unit- like the energy consumption in production. This property of production systems is often discussed isolated in the domain production (system) development. By integrating both domains, a huge benefit could be generated if suitable tools are available in order to support this situation.

The analysis of the state-of-the-art in integrated product and production (system) development shows a deficit of fully integrating methods and process models. There are several approaches that bridge both spheres but only in one direction. Integration from an organizational view is already often implemented in big companies, but the methodical support is underdeveloped. There is a huge need

for tools that enable an integrated view on the principle solutions of the product and the production in order to evaluate the best overall solution for the lifecycle.

The authors introduce a new method called "Integrated Morphological Chart" that provides the claimed evaluation possibility. Different principle solutions for the product functions are assessed with different principle solutions of the function of a corresponding production system. The Evaluation is not limited to one target, like the minimization of the energy consumption in production, but takes also other constraints like costs or technical functionality into account. The weighted results of the targets are summarized to a total score. This tool is designed to help the developers of both domains selecting the right characteristics in early phases of the product creation process, according to different constraints depending on the philosophy of the company. The described method represents, at first, one solution for the desired feedback in figure 1.

Future research will detail the presented method by including additional environmental impact categories. The validation of the method on an existing use case from automotive assembly, which focuses on cross domain energy efficiency, is ongoing. Furthermore other methods or tools will be developed to close the feedback circle. In order to ensure the applicability of the method in industry, a software tool will be developed by the authors, basing on the theoretical principles of this contribution.

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