



Necessity of a multi-dimensional approach in the development of modular product families

Marc Zuefle¹, Florian M. Dambietz², Dieter Krause³

¹Hamburg University of Technology (TUHH), Institute for Product Development and Mechanical Engineering Design; marc.zuefle@tuhh.de, corresponding author

²Hamburg University of Technology (TUHH), Institute for Product Development and Mechanical Engineering Design; florian.dambietz@tuhh.de

³Hamburg University of Technology (TUHH), Institute for Product Development and Mechanical Engineering Design; krause@tuhh.de

Abstract

The development of modular product families in the context of cyber-physical mechatronic systems requires a more widespread integration of development and organization-related requirements for the value creation of such systems. In this context, the focus of consideration is increasingly shifting to the development and design-relevant disciplines in order to be able to address requirements in product development in a multi- and also cross-disciplinary manner. This new focus means that modular cutting should not be implemented purely mechanically. An example of laser cutting optics is used to show how design for variety methods can generate benefits over several levels and life phases by multi- and cross-disciplinary approaches. The given basic system is analyzed and visualized by these methods. Subsequently, the system under consideration is conceptually considered in a multi- and cross-disciplinary context adapted by these methods to analyze to what extent a module cut can be supported by it on a mechatronic level. The result of this conceptual approach shows potentials in the multi- and cross-disciplinary implementation of such methods, which substantiates the examination of different systems with an additional focus on development-specific disciplines. Likewise, however, the conceptual approach also reveals the additional gaps which need to be analyzed in subsequent research and addressed by devised solutions.

Introduction

Within the modern globalized economic market behaviours, customer tend to request an ever-increasing degree of customized products being adapted to their specific needs. On the other hand, these specific adaptations are not to come with an increase in the overall product cost. Therefore, a strong pulling factor for today's product architecture is their effectiveness considering their development, manufacturing and the resulting overall cost (Verband Deutscher Maschinen- und Anlagenbau 2014). In order to react to these seemingly opposing challenges modern markets impose towards companies, one reliable and proven approach is supplied by the concept of modularization (Dieter Krause et al. 2018). By evolving the product architecture from a grown and probably unstructured architecture towards a methodically developed and therefore modularized product architecture, the five main company-internal goals for targeting the customer and market requirements can be achieved, with these main goals being function-binding, de-coupling, configurability, interface standardisation and component standardisation (Salvador

2007). Based on these five general rules, almost every individual methodical approach for the development of modular product architectures is created. These approaches can significantly differ in term of their orientation and focus during the development of such modular architectures, with on the one hand focusing mainly on technical-functional modularization aspects. On the other hand, other tend to focus more on the product strategic perspective of modular product architectures. As these two main streams both identify different, but still important module drivers, there exist approaches intending to combine the best of both worlds, which conclude technical-functional modularization as well as product strategic aspects amongst all different individual product life phases.

Nevertheless, all these approaches have been designed with the idea to modularize mechanical products, with electrical, fluidic or software control aspects being considered as standardized components. This leads to modular product architectures being set-up mainly on the basis of their mechanical interaction situation. This aspect can lead to significant challenges when intending to modularize product architectures for mechatronic instead of mechanical products, or, even worse, for Cyber-Physical-Mechatronic Products. As these products contain a high degree of their composition and for their added value from the electronic or software part instead of the mechanical part, applying methods being based on purely mechanical products does not seem to produce holistically adequate results. This is further encouraged by the fact that within modern high-tech machine building, the mechanic set-up in reality is significantly less function-generative than the corresponding electronic and software control part.

At this point, we propose the hypothesis, that methods being specifically designed to support the development of mechatronic products or CPMS can provide a significant improvement in the overall performance of the modular product architecture. This contribution therefore tries to show the gap of the existing methods as well as the exemplary problem description using a product example of laser cutting optics.

Research Background

The relevant literature for this contribution can be split into two subsections, with the first part defining the scope of interest and therefore the Cyber-Physical Mechatronic Systems. The second part consists of the existing methods for the modularization of product architectures with respect to their specific orientation, as already mentioned in the introduction.

On the one hand, there is relevant basic literature dealing with change and the requirements for the development of technical systems (Lee et al. 2015; Lidong et al. 2016), which are also a basis for the draft of the new norm VDI 2206 for developing cyber-physical mechatronic Systems. Thereby literature is also considered, which addresses Cyber-Physical Mechatronic Systems (CPMS) and their impact into both engineering design and production (Tomiya et al. 2019). CPMS have a fundamental role in this elaboration because their enhancement can be put in relation to mechanical systems, and this can be done equivalently with the considered methods.

The relevant methodical literature forms the second subsection of the considered literature and deals with the methodical approach to the development of modular product families.

Common examples for technical-functional approaches are the Theory of Modular Design according to STONE (Stone 1997), the Design Structure Matrix (DSM) according to Pimmler and Eppinger (Pimmler 1994; Eppinger et al. 2012). On the other hand, purely product strategic methods are described by the Modular Function Deployment by Erixon (Erixon 1998) or the Life Phases Modularization (Kipp et al. 2010). By implementing parts from both different approach perspectives, so-called integrated methodical approaches have been generated. Common examples therefore are given by the Product Family Master Plan (PFMP) by Simpson (Simpson et al. 2012) or the Integrated PKT-Approach (Dieter Krause et al. 2018).

For this presented research, we use the basic principles and methods of the Integrated PKT-Approach with its main aspect of the Life Phases Modularization. One key aspect of the Integrated PKT-Approach is its composition as a methodical toolkit, where the individual methods and method parts can be used for the underlying relevant modularization task. This approach is mainly based on a consideration of all product life phases from product development to recycling and intends to develop individual modular architectures for each life phase, which are then reconciled by an expert team into one final modular product architecture. This step is called *Harmonization* (Krause et al. 2018; Greve et al. 2020). Prior to these steps, the existing product architecture undergoes a technical-functional Design for Variety in order to create a basis for the upcoming modularization process. All these steps are supported by individually designed methodical tools, such as the *Variety Allocation Model* (VAM) used during the *Design for Variety*. By linking customer-relevant properties over working principles to individual components and displaying the individual connections by lines, it allows for a proper identification of main target points for the Design for Variety process. The *Module Interface Graph* (MIG) on the other hand, supports the visualization of the interconnections and the degree of variance within product architectures by displaying the product in a cross-section drawing like manner, where variant components are symbolized in grey and standard components are shown in white. The individual flows between components, such as mechanical connections, fluid or information flows are displayed with individually colored arrows. Further information considering these two specific methods can be found in Krause & Gebhardt (Krause et al. 2018; Rennpferdt et al. 2020).

Nevertheless, both integrated approaches, the PFMP as well as the Integrated PKT-Approach are mainly focused on a product development-based modularization process originating from the mechanical perspective. This may be the proper orientation when modularizing simple mechanical products, but when it comes to Cyber Physical Mechatronic Systems, this orientation lacks significantly in the holistic implementation of all relevant product development disciplines.

The following figure displays the lack of cross-disciplinary methods or a focus shift from mechanical to e.g. software based or electronic based or even mixed view for an MPA development.

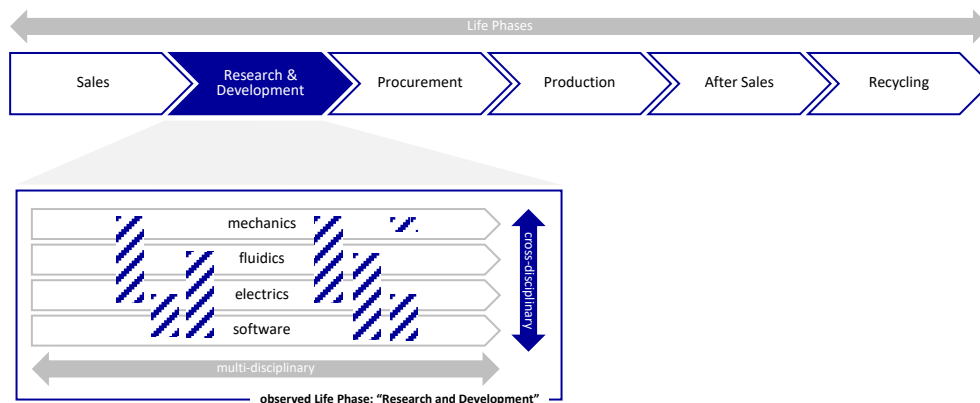


Figure 1 – illustrative multi- and cross-disciplinary consideration in the context of life phases

Many methods for developing modular product families often refer to the combination of mechanical components and assemblies in module design. In Design for Variety mechatronic systems are often considered but optimized on the basis of the mechanical components. Immaterial and mechatronic components often not considered thereby specifically. Within this contribution, we intend to present the origination and first views to a more precise view on discipline levels (multi-disciplinary) and mapping of dependencies (cross-disciplinary), which will have to be examined in close detail.

Exemplary Analyzed System

The laser cutting unit of a machine tool manufacturer was chosen as an exemplary investigation system. This system is very well suited for the investigations carried out here, since many development disciplines have both influences, in the sense of direct participation, and requirements, for example via neighboring assemblies and interfaces.

In this example, the laser cutting unit under consideration is first analyzed according to Kipp's *Design for Variety* method. This method makes it possible to identify links across different levels of the product under consideration, to display them visually in a so-called *Variety Allocation Model* (VAM) and also to analyze them. (Kipp et al. 2010)

The exact and step-by-step procedure of the method is left out of this publication, as it is a conceptual work in which the method is to be used as a tool for implementation and presentation. Nevertheless, the rough process is outlined in order to be able to understand the procedure.

The Laser Cutting Unit system was analyzed on different levels. Firstly, sales and product management identified the variant-relevant product characteristics, creating the first level in the Variety Allocation Model shown in Figure 2. Then, in architecture management, the product architecture was examined and the corresponding characteristics were identified, which are influenced by the selected variant customer-relevant characteristics. These characteristics form the second level in Figure 2. Finally, the variant components are analyzed and visualized in the Variety Allocation Model. The variant components are identified via a so-called *Module Interface Graph* (MIG), which is shown in Figure 3 on the right, using the Laser Cutting Unit as an example.

The *Variety Allocation Model* and the *Module Interface Graph* play a crucial role in this conceptual analysis. For this reason, the *Variety Allocation Model* is briefly discussed in Figure 2, followed by a more detailed discussion of the *Module Interface Graph* in Figure 3.

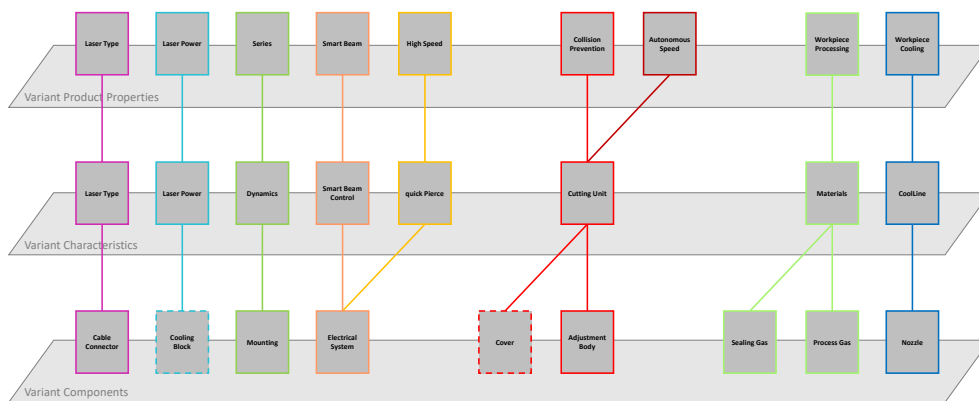


Figure 2 – simplified Variety Allocation Model (VAM) of the exemplary Laser Cutting Unit

As can be seen in Figure 2, the *Variety Allocation Model* consists of a few strands, which go over all three levels and are interwoven as little as possible. When applying the *Design for Variety* method according to Kipp (Kipp et al. 2010), such a representation is desirable. This visualizes that a variant component is only influenced by a single variant product property, which keeps the internal variety as low as possible. In addition, it is noticeable that the data of the variant components are mainly of mechanical definition. It was described at the beginning that the functionality of a mechatronic system is not only implemented by mechanical components, but increasingly by additional disciplines such as software or electrical engineering.

This realization leads to the fact that we want to examine that, in how far other development disciplines and their components into the consideration of the variant formation with flow, and/or can.

For this purpose, we will take a closer look at the *Module Interface Graph*, as shown in Figure 3 on the right. The *Module Interface Graph* visualizes the variant components that are represented in the *Variety Allocation Model*. In this case, the information for the *Module Interface Graph* was drawn from three different sources. Firstly, the CAD model of the respective variant was analyzed, secondly, interface documentation was used and thirdly, Engineering-BOM and Manufacturing-BOM were read out. The result of the analysis is shown in Figure 3 on the right as a module interface graph. The purpose of this representation is to highlight in gray where variant components and groups are transferred to the VAM. If you look at the *Module Interface Graph* shown here, you will see few gray areas and many white, i.e., standard components.

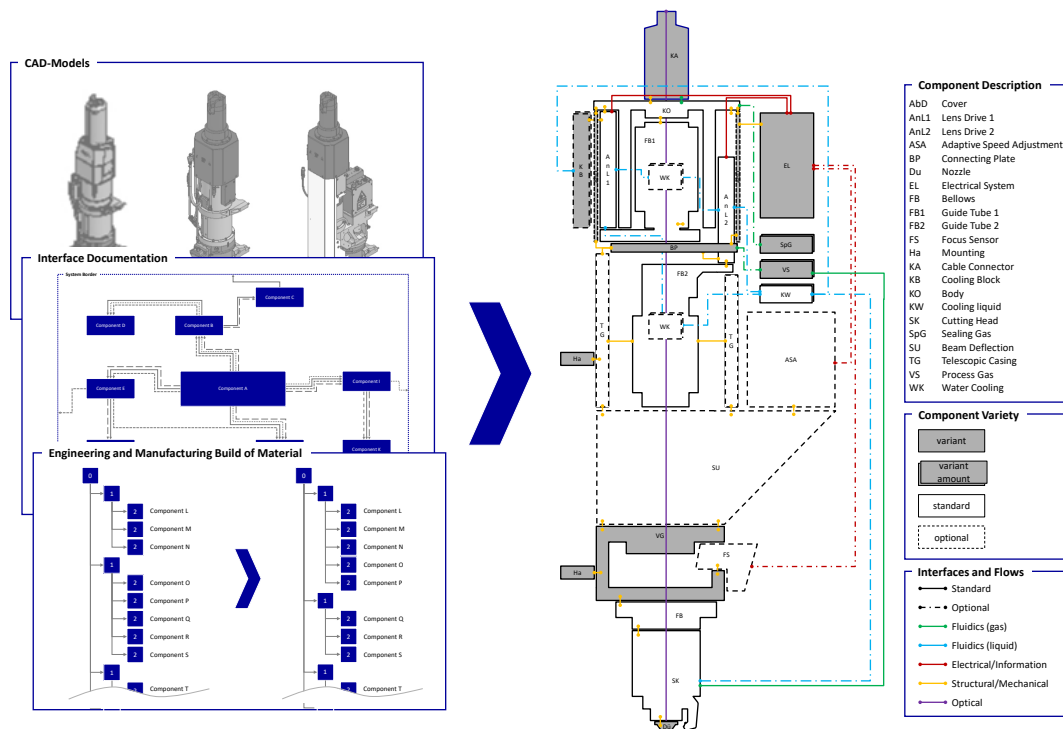


Figure 3 - Module Interface Graph (MIG) of an exemplary Laser Cutting Unit and its basic information (simplified due to IP-issues)

The hypothesis of concentrating on mechanical components can be proven for the *Module Interface Graph* drawn up here. In addition, it can be seen that the *Module Interface Graph* from Figure 3 was derived based on mechanical principles.

The hypothesis following from this:

- In order to be able to analyze and optimize the design for variety of cross-disciplinary structures, the development disciplines involved must also be integrated holistically into the analysis and be represented in it.

Concept of a multi-dimensional approach

From the previous chapters of this publication, it could be deduced that the systems in product development and thus also in the development of modular product families are becoming steadily more complex. Reason for it are the rising interactions of the functionality-determining development disciplines. Many of the methods for the analysis of the *Design for Variety* are thereby however

concentrated on mechanical components. For this reason, this chapter attempts to apply the *Design for Variety* method already presented to a cross-discipline system.

The idea behind this is that a complicated system, as described in systems theory, can be broken down into simpler subsystems, on the basis of which the existing methods are carried out and then combined again to form an integrated system. This conceptual attempt is further considered and analyzed using the Laser Cutting Unit of a laser machine manufacturer as a preceding example. The disciplines of mechanics, electrics, fluidics and software development are specifically considered and integrated into the method of *Design for Variety* according to Kipp (Kipp et al. 2010). This variant-oriented design is analyzed and compared with the previous presentation of the holistic system.

The analysis of the discipline-specific components requires additional sources of information to those already mentioned in Figure 3. For this, however, it must first be understood which information and components the individual disciplines bring into the system and how these are documented. An excerpt of this information is shown in the following table.

Table 1 - relevant Information for creating a cross-disciplinary MIG identified from exemplary environment

Engineering Discipline	Relevant Informationen for multi-disciplinary MIG
Mechanics	<ul style="list-style-type: none"> - CAD Model - Interface Documentation - Build of Material
Elektrics	<ul style="list-style-type: none"> - Master Electrical Layout of regarded Product - Interface Documentation
Fluidics	<ul style="list-style-type: none"> - Master Fluidical Layout of regarded Product - Interface Documentation
Software-Development	<ul style="list-style-type: none"> - Logical Sequences incl. Error Information - Input-Output List

With the help of this information, the cross-departmental *Module Interface Graph* (X-MIG) is created and later transferred to the already created Variety Allocation Model from Figure 2. The creation of the cross-departmental *Module Interface Graph* poses some challenges. Namely, additional notations and representations have to be included to represent the additional information. Due to the conceptual nature of the representation derived here, additional iterative steps must be taken downstream to optimize the representation. However, for the purpose of a first concept needed here, the result and its usefulness will be considered first.

Figure 4 shows a first concept of a cross-disciplinary *Module Interface Graph*. Here, different colors illustrate different development disciplines, which are to be selected from application to application. It is important here that the notations for the variant components remain and thus the graph retains its original function and is extended by a cross-disciplinary representation.

If the identified variant components of the individual disciplines are transferred, the Variety Allocation Model can also be extended. One challenge here is with mixed components, i.e., components which cannot be clearly assigned to a discipline, or which must be split by further splitting into discipline-specific components. However, this challenge also underlines the possibility, which is offered on the level, by being able to represent the interactions and dependencies of different disciplines from each other. Thus, components with a cross-disciplinary character can be identified.

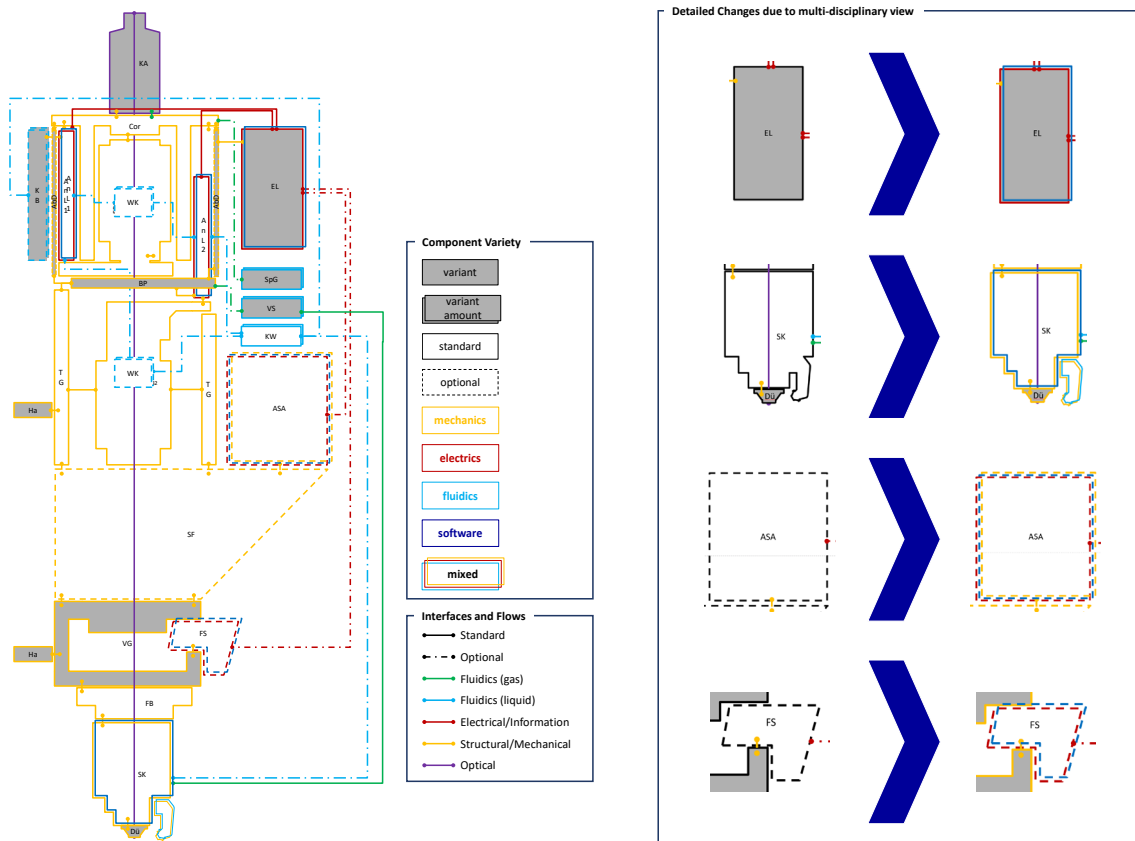


Figure 4 – conceptual Module Interface Graph with discipline-specific components and four examples of changed visualization

In the new Variety Allocation Model in Figure 5, the newly identified components are represented in a multi-disciplinary representation on the third level. Multi-disciplinary because the discipline-specific components are first considered in parallel. Similar to Figure 1, Figure 4 also shows that a cross-disciplinary character is created by considering all levels. Looking more closely at the updated Variety Allocation Model, we see a change in the number of components and the allocation to the variant customer-relevant product characteristics. The color clusters remain the same, but the number of connections between the levels increases, which also increases the internal variance considered. This is because the more connections between the levels, the more internal combination possibilities there are based on a product characteristic.

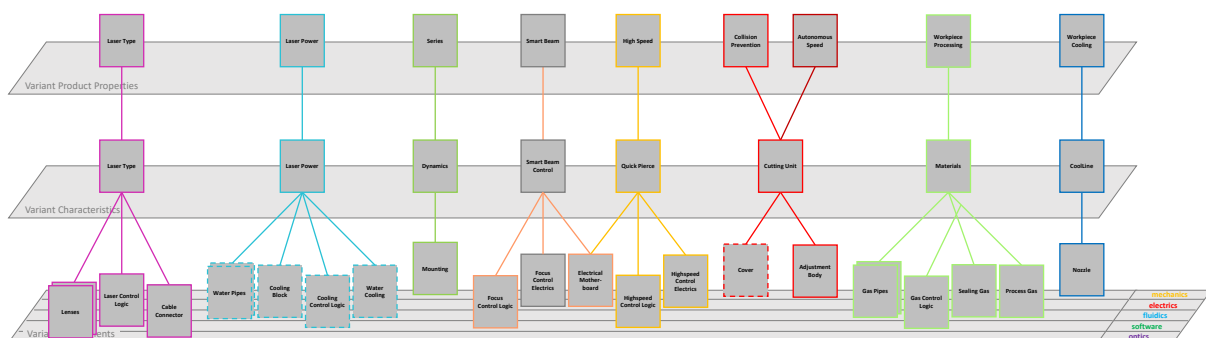


Figure 5 - Variety Allocation Model with exemplary discipline-specific splittet components

In further steps of the method of the Design for Variety by Kipp now optimized concepts would be shaped and validated and discussed with the developers concerned. Since this conceptual investigation refers

however to the representation of cross-disciplinary structures by existing methods of the development of modular product families, this point of the completeness is touched in the following only briefly.

As can be seen in Figure 5, the variance exists mainly at the component level. Here it can be identified that for example a software logic is variant for a product characteristic. This insight could not be gained from the previous Variety Allocation Model in Figure 2. Thus, there is already an advantage here in the consideration of the system. Another example is cabling and hoses.

This provides the insight that variety-oriented design can be considered based on the system theory, but additional framework conditions have to be considered and further investigated. One problem analyzed is the interactions between the individual discipline levels, which must be represented in order to consider the overall system. The exemplary representation also shows that it has to be investigated which levels of variant-oriented design have to be split up and which have to be included in the overall system. A major conclusion is that the splitting of a system into disciplines and the multidisciplinary view can bring advantages. However, problems arise in the combination to a cross-functional system, in which the knowledge of all individual disciplines is linked to an overall system.

Critical Reflection of the Concept

According to Eigner (Eigner et al. 2014), more and more functions of a modern machine system are targeted not via classical hardware solutions, but by implementing highly sophisticated software solutions. The underlying hardware needs of course to be designed adequately in order to be able to convert the software instructions into real functions, but in most of these cases, the main issue and problem solving comes with the main software solution. Therefore, when considering the above-displayed modularization methods and -visualizations, it is to be considered that the purely hardware-based approach and colours need to be changed towards software-based methods and therefore visualization colours. We consider that issue as partially true with the exclamation, that also further aspects and developments need to be taken into account.

When considering the above-used product example for the evaluation of the contributed concept, we only used a small part of the available information, which was a sufficient amount in order to display the basic principle and its applicability. Nevertheless, there is a significant number of still to be improved aspects. On the one hand, the analysis as well as the method for the identification of discipline-specific components, such as the determination whether a pump is e.g. a mechanical or fluidic component. Furthermore, it needs to be analysed whether software is always an immaterialized component or if it can be linked to the existing definition of a component.

When it comes to the presented concept, it needs to be stated that it is still at a quite simplified level, but already creates several benefits for the understanding of a multidisciplinary system. Nevertheless, we see significant areas for improvements, especially in the areas of the visualization. The interference between different components and disciplines needs to be shown, as this the point where the change from multidisciplinary towards cross-disciplinarity appears. Until now, this does not appear in the presented visualization and therefore will be part of the future work.

In the following, a brief discussion and outlook for this contribution is presented.

Discussion and Outlook

The research discussed here is intended to show that existing methods can be used for the manageability of complicated to complex systems. Thereby it is shown that the splitting in multi-disciplinary processing achieves a reduction of the complexity, which can bring an added value for the development of e.g., CPMS. This results in the contribution that existing methods can be analyzed to investigate the performance of

these methods in the system context regarding possible makeability. However, it should be noted that the interactions between the emerging subsystems must be additionally mapped. This mapping has to be investigated in further research, as already mentioned while critical reflecting the shown concept. In conclusion, the findings offer a possible prelude to investigate and advance the readiness for CPMS in modular product development and also additional product life phases.

For practical application, it can be concluded that various methods, which seem too extensive for big systems, may be able to add value more rapidly at the sublevel. In addition, it can be assumed that the splitting creates the possibility that the know-how sources in the special domains can implement the methods more quickly and more effectively than before. For example, in further research it should be analyzed how the method shown here works, while regarding only discipline-specific subsystems. This is an additional possibility in investigating variety on multi-disciplinary level and afterwards merging it to a cross-disciplinary structure with extra regarded dependencies between the single discipline-specific levels. However, these statements are only assumptions, which are made from the exemplary case and must be proven or disproven in further investigations.

Literature

- Eigner, M., D. Roubanov, and R. Zafirov. 2014. *Modellbasierte Virtuelle Produktentwicklung*. Berlin, Heidelberg: Springer Berlin Heidelberg.
- Eppinger, S. D., and T. R. Browning. 2012. *Design Structure Matrix Methods and Applications*: The MIT Press.
- Erixon, G. 1998. *Modular Function Deployment: A Method for Product Modularisation*. TRITA-MSM 98,1. Stockholm: The Royal Inst. of Technology Dept. of Manufacturing Systems Assembly Systems Division. Zugl. Stockholm, Kungl. Tekn. Högsk., Diss., 1998.
- Greve, E., C. Rennpferdt, and D. Krause. 2020. "Harmonizing Cross-Departmental Perspectives on Modular Product Families." *Procedia CIRP* 91:452–57. doi:10.1016/j.procir.2020.02.198.
- Kipp, T., C. Blees, and D. Krause. 2010. "Anwendung Einer Integrierten Methode Zur Entwicklung Modularer Produktfamilien."
- Krause, D., and N. Gebhardt. 2018. *Methodische Entwicklung Modularer Produktfamilien*. Berlin, Heidelberg: Springer Berlin Heidelberg.
- Lee, J., B. Bagheri, and H.-A. Kao. 2015. "A Cyber-Physical Systems Architecture for Industry 4.0-Based Manufacturing Systems." *Manufacturing Letters* 3:18–23. doi:10.1016/j.mfglet.2014.12.001.
- Lidong, W., and W. Guanghui. 2016. "Big Data in Cyber-Physical Systems, Digital Manufacturing and Industry 4.0." *IJEM* 6 (4): 1–8. doi:10.5815/ijem.2016.04.01.
- Pimmler, T. U. 1994. "Integration Analysis of Product Decompositions." In *ASME Conference on Design Theory and Methodology*. Minneapolis, MN, 343–51.
- Rennpferdt, C., and D. Krause. 2020. "Towards a Framework for the Design of Variety-Oriented Product-Service Systems." *Proc. Des. Soc. Des. Conf.* 1:1345–54. doi:10.1017/dsd.2020.108.
- Salvador, F. 2007. "Toward a Product System Modularity Construct: Literature Review and Reconceptualization." *IEEE Trans. Eng. Manage.* 54 (2): 219–40. doi:10.1109/TEM.2007.893996.
- Simpson, T. W., A. Bobuk, L. A. Slingerland et al. 2012. "From User Requirements to Commonality Specifications: An Integrated Approach to Product Family Design." *Res Eng Design* 23 (2): 141–53. doi:10.1007/s00163-011-0119-4.

Paper submitted to and accepted after peer-review:

R&D Management Conference 2021 "Innovation in an Era of Disruption"; July 6th-8th 2021, Glasgow, SCO

Stone, R. B. 1997. "Towards a Theory of Modular Design." Dissertation, The University of Texas.

Tomiyama, T., E. Lutters, R. Stark, and M. Abramovici. 2019. "Development Capabilities for Smart Products." *CIRP Annals* 68 (2): 727–50. doi:10.1016/j.cirp.2019.05.010.

Verband Deutscher Maschinen- und Anlagenbau. 2014. *Zukunftsperspektive Deutscher Maschinenbau*. Frankfurt/Main.