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Coping Asynchronous Modular Product Design by Modelling a Systems-in-System

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Abstract

This paper analyzes the potential of crossdisciplinary collaboration in the methodical development of Modular Design by harmonization asynchronous mechatronic system structures. Subsystem boundaries in multidisciplinary development processes are set disciplinespecific, resulting in inconsistencies in module fitting. Based on a case study, harmonization of disciplines is elaborated as a solution. This aligns discipline structures and reduces effects on the variety in system structures.This implementation shows support for modular design and enables an integrated view as a systems-in-system.

Keywords: *modular design, complex systems, multi-/cross-/trans-disciplinary approaches, collaborative design, system of systems*

1. Introduction

The motivation for the topic of this paper is based, among other things, on field observations in which increasing flexibility and customer individualization have an impact on the design of mechatronic systems and modular product families (Albers *et al.*, 2018; Kuhl *et al.*, 2021). In addition, manufacturing companies are facing highly competitive pressure induced by long-term megatrends such as increasing globalization or an accelerated technology cycle (Krause and Gebhardt, 2018). Market pressures and new business models to meet these requirements also change the way system architecture design is considered (Skogstad *et al.*, 2022; Gauss *et al.*, 2022; Seiler *et al.*, 2019; Wynn, 2010). Increasing customer individualization has an impact on product diversity and thus also on the handling of increasing internal diversity as well as the complexity induced by this within the company itself (Hansen *et al.*, 2022; Kuhl *et al.*, 2021; Krause *et al.*, 2014). The required flexibility affects collaboration and design in the development process across life phases (Blees *et al.*, 2010; Greve *et al.*, 2020). Thus, not only individual adaptability of product features is part of flexibility, but also fast maintainability (life phase: service) or continuous upgradeability (life phase: sales) (Abramovici *et al.*, 2017; Seiler *et al.*, 2019). New business models, such as Everything-as-a-Service (XaaS) require additional cross-departmental and cross-disciplinary collaboration to meet the new requirements in a target-oriented manner (Rennpferdt and Krause, 2020; Zuefle *et al.*, 2021b).
Many of the pressures mentioned can be addressed by developing modular product families. In doing so, the development of modular product families reduces internal variety while maintaining or increasing external diversity, which can make complexity more manageable within the company itself (Krause and Gebhardt, 2018). In addition, the life phases upstream and downstream of the development are integrated into the structuring of the product architecture, whereby a harmonization of the system structure can be achieved (Greve *et al.*, 2020; Blees *et al.*, 2010).
Various development methodologies show an enhanced integration of multi- and cross-disciplinary approaches over the past years (Graessler *et al.*, 2018; Walden *et al.*, 2015; Vasić and Lazarević, 2008).

Due to a growing share of software the composition of mechatronic systems, or rather the implementation of the functionalities and properties are highly dependent on the collaboration of different development disciplines (Tomiyama *et al.*, 2019; Abramovici *et al.*, 2017).
Altogether, it can be concluded from the trends and situations presented that collaboration across disciplines is becoming increasingly relevant in the development of mechatronic systems. This also opens up the question of how different approaches can be placed in such a context. In the following, this question will be examined based on the development of modular product families and a case study. First, the relevance of the investigation will be presented through a literature review and then an established approach will be used as an exemplary case. The procedure and the results are subsequently examined critically, and conclusions are derived from them.

2. Research Background

Literature research was conducted as basis for this elaboration. The research was aimed at analyzing the main aspects addressed in the introduction, such as the development of modular product families, multi-disciplinarity, cross-disciplinarity and different development disciplines in their mutual interaction.
For this paper, the focus of interest will be on the development of modular product architectures when it comes to the term Modular Design. The key point is the methodical approach to bundle different components of a system, according to technical-functional and product-strategic aspects and the preceding Design for Variety.

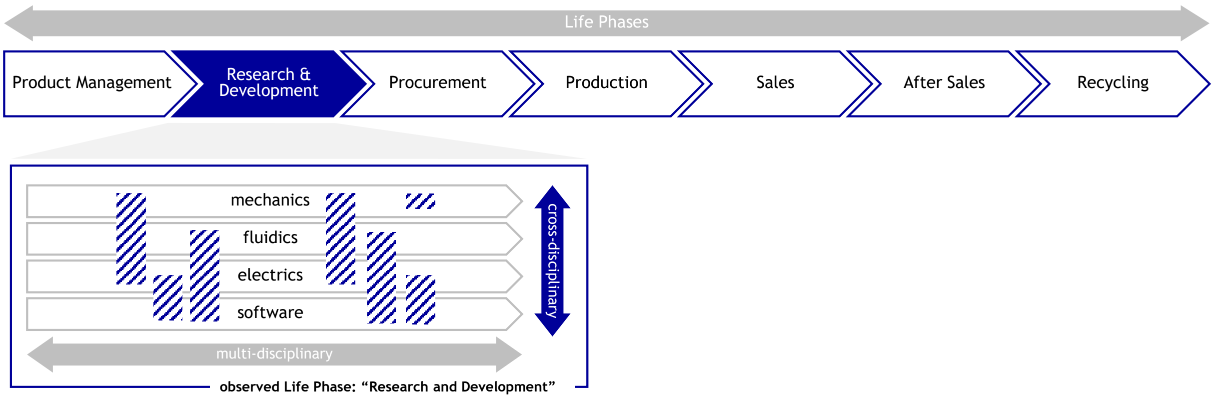

Figure 1. Visualization of selected multi-disciplinarity in exemplary product life phases extended with cross-disciplinarity by Zuefle et al. (2021a)

Multi- and cross-disciplinarity are treated in this paper as specifications of interdisciplinarity. Thereby, multi-disciplinary structures are defined as parallel, interrelated, but predominantly independently developed designs for this paper. Cross-disciplinary structures extend these parallel designs to include cross-cutting exchanges, whereby not only information, but also methods and concepts are exchanged. Figure 1 illustrates an exemplary view of this definition.
The research was performed in the scientific databases Scopus and Web of Science, based on keyword narrowing with subsequent investigation on selected papers based on abstract reviews. To get an overview of the extent to which cross-disciplinary collaborations, or perspectives are addressed in the development of modular product families, different research steps were taken.
First, methods for the development of modular product families were researched and analyzed. There are numerous established approaches or methods, which concern themselves with the structuring of a modular product architecture. On the one hand there are technical-functional approaches, like the Design Structure Matrix by Pimmler and Eppinger (1994) or the theory of the Modular Design by Stone (1997). There are also approaches that represent the product-strategic view, such as Modular Function Deployment by Erixon (1998) or Life Phase Modularization by Blees *et al.* (2010). In addition, there are also approaches that combine both views, such as the Product Family Master Plan (Simpson *et al.*, 2012) or the Integrated PKT Approach (Krause and Gebhardt, 2018).

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Based on this, the importance of multi- and cross-disciplinarity in those modular design approaches was investigated. It was found that the terms multi-, inter-, trans- as well as cross-disciplinarity result in a strong limitation of the search results, as can be seen in Table 1.

Table 1. Exemplary Scopus query string for specified literature research (as of 02/22/2022)

Query String	Step	Results
TITLE-ABS-KEY *(" modular* design " **OR** " modular* architecture ")*	**(I)**	14.876
(I) ***AND*** *(* ***LIMIT-TO*** *(SUBJAREA , "ENGI"))*	**(II)**	8.468
(II) ***AND TITLE-ABS-KEY*** *(" multi-disciplin* " OR " multidisciplin* ")*	**(III)**	42*
(II) ***AND TITLE-ABS-KEY*** *(" inter-disciplin* " OR " interdisciplin* ")*	**(IV)**	19**
(II) ***AND TITLE-ABS-KEY*** *(" trans-disciplin* " OR " transdisciplin* ")*	**(V)**	5***
(II) ***AND TITLE-ABS-KEY*** *(" cross-disciplin* " OR " crossdisciplin* ")*	**(VI)**	1****

**17 results in field of modular product design.*

***9 Results in Modular Product Design; Interdisciplinarity is mostly life cycle or educational perspective.*

****one finding with reference to intelligent modular product architectures.*

*****finding inadequate due to abstract review. In field of general "product development", the results increase to 66 with regards to knowledge exchange and collaboration in complex systems.*

Due to limitations of the paper this section concentrates on specific findings in the literature review based on the different disciplin aspects and views. Further information about methodologies and content of the reviewd papers can be traced via the search strings if required.

As a result of the literature research on overarching considerations in the development of modular product families, it can be concluded that many publications deal with multi-disciplinarity, which addresses a parallel design at level of the development disciplines. Examples given here are Mcharek *et al.* (2019) und Mensing and Schaefer (2015). Regarding interdisciplinarity, an inconsistency can be observed in terms of perspective. For example, the keyword interdisciplinarity is often understood to include a consideration of the life phases in product engineering, as well as a reference to engineering education (Eigner *et al.*, 2014). Nevertheless, there are also considerations of the collaboration of development disciplines (Birk *et al.*, 2021). Cross-disciplinarity shows a relevant concretization here but is not really used in the context of modular design. The relevance of the topic can be illustrated, however, if cross-disciplinarity is considered at the level of product engineering (for example see Figure 1). In this context, it is increasingly addressed that cross-disciplinarity is a necessary dimension for coping with the development of complex systems (Friedl *et al.*, 2016; Hehenberger and Zeman, 2005; Thramboulidis, 2005) and also modular design (You and Smith, 2016). Thus, it can be concluded that it has equally a relevance for the development of modules as complex subsystems of complex systems.

To be able to assess the need for a cross-disciplinary view also on the subsystem level of a product/system and thus also on Modular Product Design, it must be clarified as an additional research background whether Modular Design is relevant in different development disciplines. For this purpose, a further literature review on discipline-specific modularization was conducted. As a result, various sources, such as Morgan *et al.* (2021), Campusano *et al.* (2021) or Liu *et al.* (2021), prove that modular design is also considered in software engineering, mentioned here as a representative of other development disciplines, due to limitations of this paper. Thus, it can be concluded that there is at least a multi-disciplinary modular design in the conceptualization of products. There is hence a need to consider the modularization of systems across disciplinary system boundaries and to identify potentials and approaches for this. In summary, the literature review shows that there is not yet comprehensive research on collaboration across disciplines in the development of modular product families or Modular Design that can be used for further research. For this reason, it is appropriate to conduct a study on cross-disciplinarity in this field.

3. Methodology

The literature review shows that there are a limited number of studies dealing with multi- and cross-disciplinarity and the development of modular product families. In addition to the keyword analysis,

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the more detailed research also revealed that the focus of the studies found was not on methodological application. However, to consider precisely this aspect of methodological support and application in a multi- and cross-disciplinary context, there is a need to analyze it. This paper limits itself to multi- and cross-disciplinarity and therefore excludes inter- and trans-disciplinarity due to the scope of the underlying case study.
Through the findings of the Research Background and the associated literature review, the following hypotheses emerge for this paper:

1. A multi-disciplinary and abreast Modular Design has to irregular module boundaries and an impaired system integration
2. A harmonization across disciplin-specific subsystem boundaries enables synergies for product system architectures
3. A cross-disciplinary harmonized Design for Variety enables synergies and potentials in product and system architectures

To investigate the hypotheses, the following chapters each address one of the mentioned hypotheses.
In chapter four, the addressed multi- and cross-disciplinarity is analyzed and put into the context of a modularization example. This example was carried out in cooperation with a German machine tool manufacturer. Besides the classification of multi- and cross-disciplinary structures, the methodological process is crucial for the analysis and will be used as a reference for further investigations. Additionally, in chapter five, the term System-of-Systems (SoS) is briefly analyzed because the term describes the ideal state of harmonized systems in a supersystem. Therefore, the ideal image of the SoS serves as a reference.
The second hypothesis is then addressed on this referencing matter. Based on the example of harmonization intersecting module boundaries, it is analyzed and shown what synergies result from this on the architecture considered in this paper
Chapter 6 addresses the third hypothesis and its validation using the case study. The findings subsequently are visualized and placed in relation to the previously taken considerations.
Finally, the results are discussed critically, and the further steps and focal points of consideration are outlined.

4. Analysis of Multi- and Cross-Disciplinarity in Modular Design

The development of a mechatronic system is a multi-disciplinary process, which involves all stakeholding development disciplines from requirements engineering to discipline-specific design (Pérez-Rodriguez *et al.*, 2018). Different development methodologies thereby address the multi-disciplinarity in the development of a mechatronic system. In this process, the requirements are decomposed via functional architectures, to logical architectures and subsequently to the discipline-specific design levels. At this design level, the processes are multi-disciplinary, which means that the individual development disciplines perform individual design activities in parallel to the other development disciplines involved. This circumstance can be embedded in the context of the product life phases (Graessler *et al.*, 2018; Eigner *et al.*, 2014) and was illustrated in Section 2 by Figure 1.
To be able to analyze and examine the potential of cross-disciplinarity in development of modular design, an applied case study of a machine manufacturer's loading and unloading automation system is used.

4.1. Introduction of the Applied Case Study

The applied case study in this paper represents the exemplary analyzed and realized system which depicts a lead example through the whole paper presented.
The example given is a product family of loading and unloading automation that uses suction cups to load sheet metal and sheet metal parts into and out of a machine tool. At the beginning of the investigation, the product family exhibits a high degree of external and internal variety, which results in high development efforts, due to changes in the periphery or in the product itself. The status quo includes several mechatronic systems in the product family, which are not structured in a modular kit. Based on this, a modular kit was developed using the Integrated PKT-Approach. The first iteration from simple mechatronic product to first modular kit of the observed system is briefly described in the following and

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considered later for the fit into the former process. In this case, the featured methods were the Design for Variety by Kipp *et al.* (2010) and the Life Phase Modularization by Blees *et al.* (2010).
As a result of the first iteration, the need for integrating additional disciplines into the design process, was revealed. Therefore, in this publication the methods used were applied and adapted to address this challenge and design a cross-disciplinary Design for Variety (x-DfV).

4.2. Multi- and Cross-Disciplinary Architectures in Modular Context

The initial situation was already touched upon in chapter 4.1. The first iteration for structuring the reference model was made using the Method of Design for Variety by Kipp *et al.* (2010) and the Life Phase Modularization by Blees *et al.* (2010). As focal method, the DfV by Kipp is used. This method enables to restructure the regarded product architecture in a variety-oriented way. Therefore the dependencies from external to internal variety are optimized as an pre-step of the technical-functional modularization (Krause *et al.*, 2014). In Figure 2, the Design for Variety is set in the context of the "RFLP"-Approach and an iterative procedure. This is based on a reference system, which in this case is the product family of loading and unloading automation. The system was split up via four levels and optimized for each variant in three concepts, one of which was selected in the end. The selection of one of these concepts is followed by Life Phase Modularization (LPM) according to Blees *et al.* (2010).

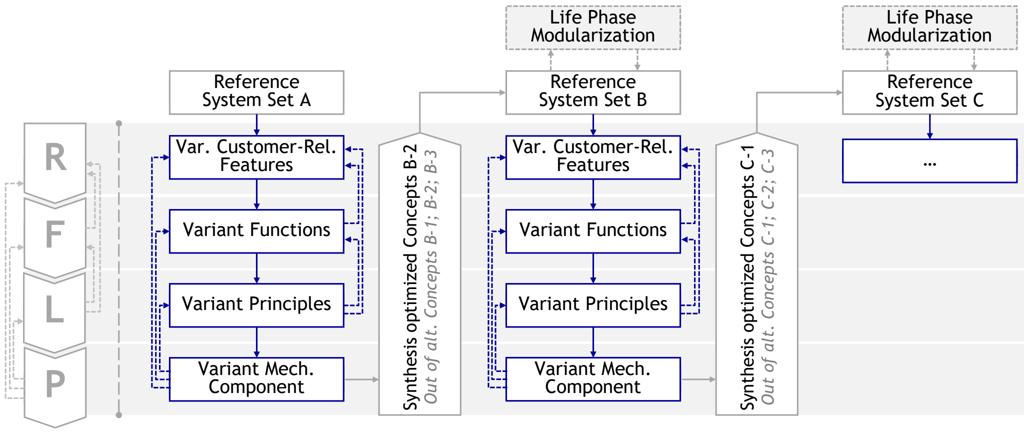

Figure 2. Design for Variety Levels by Kipp *et al.* (2010) extended in the context of the RFLP approach and an iterative procedure. Additionally linked to LPM by Blees et al. (2010).

In the first iteration of Design for Variety, various challenges of integrating further disciplines into the product were identified. For example, the product architecture on the mechanical side was designed to be strongly variety-oriented and many synergies were used, but other development disciplines designed different system boundaries in structuring their architecture.

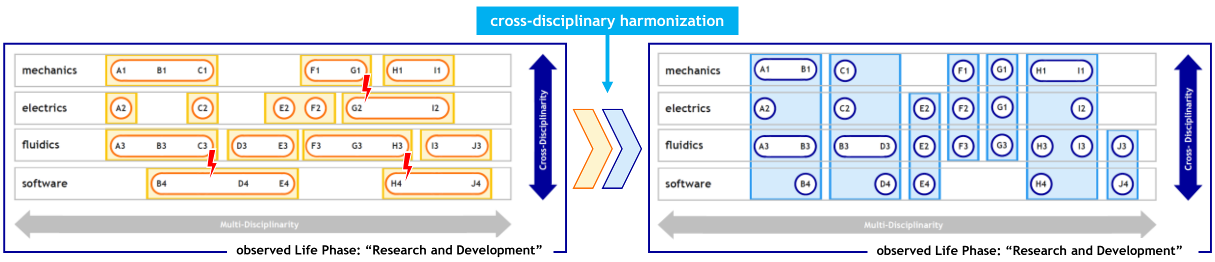

Figure 3. Conceptually cross-disciplinary harmonization (left to right) based on previous multi-disciplinary design process (left).

These different system boundaries are exemplary visualized in Figure 3 on the left. In the case study described, this led to problems and the creation of variants in the implementation of the discipline-specific designs in the overall product. For example, the product architecture is designed to be mechanically oriented and variant-oriented, but not across the disciplines. If the subsystem boundaries were harmonized, i.e., adapted to another, synergies could possibly be enabled across the disciplines, as

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can conceptually be seen in Figure 3 (right). Supporting this Figure, in the case study presented, coordination was often necessary, especially between mechanics, fluidics, and software since different key aspects were considered. In mechanics, for example, focus was placed on the dynamics of the axis, whereas in software emphasis was placed on the process of gripping. Additionally, in fluidics focus was placed on ensuring that different variants could be optimally lubricated. This resulted in different subsystem boundaries, which, due to interactions with each other, lead to an increased development effort for changes or adaptations. The conceptual adaption on regarding different discipline-specific components in the conducted case study corresponds to an variation of Life Phase Modularization by Blees et al. (2010), which runs one level higher than the development disciplines and aims for cross-departmental harmonization (Krause and Gebhardt, 2018). By this means, different drivers of specific development disciplines can be considered and integrated into the design process. This is abstractly done next.

5. Harmonizing different Development Disciplines for Synergies

If the multi-disciplinary structures shown in Section 4 are harmonized, independent subsystems across various disciplines can emerge. In the context of autonomous and independent systems, systems engineering uses the term systems-of-systems (SoS), which roughly refers to the fact that a combination of several autonomous systems is itself a system. An example of this is an aviation control system, which consists of, again, independently operating systems aircraft and helicopter. (Walden *et al.*, 2015) This brief outreach of systems-of-systems points out an interesting feature of the fractal character described by systems theory. In this paper, however, the view is not out of the product into its ecosystem with other systems, but into the product as an ecosystem itself. It is assumed that systems-of-systems provides a good reference for in-product consideration. However, due to the increased dependency in a product as a system itself, it is not entirely possible to meet all the requirements of a system-of-systems. For this reason, cross-disciplinary harmonization is used to design subsystems that approach the properties of SoS without becoming a SoS. This results in "SoS-alike" Systems-in-System (SiS). SiS are ment to be variant-oriented mechatronic subsystems which can be developed, adapted, and transferred relatively autonomously from other subsystems. These properties in turn have an impact on the higher-level life phases through improved maintainability and plug-and-play upgradability.

To achieve harmonization of the subsystems, the architectures of the development disciplines must be considered in a common method. For this purpose, the Method of Design for Variety by Kipp et al. (2010) is suitable, since this method is, on the one hand, an established procedure for variety-oriented product design (Krause *et al.*, 2021) and, on the other hand, can be placed in the context of the "RFLP"-Approach, which has already been successfully used in systems engineering for "interdisciplinary" product engineering. (Eigner *et al.*, 2014) To map cross-disciplinarity in the Design for Variety method, components from other development disciplines must be considered in addition to the standard integrated and considered mechanical components. It should be explicitly noted that the integration does not replace discipline-specific development processes but is only intended to represent an integrated visualization of the interactions between variant components to be able to structure the common product architecture in a variant-oriented manner.

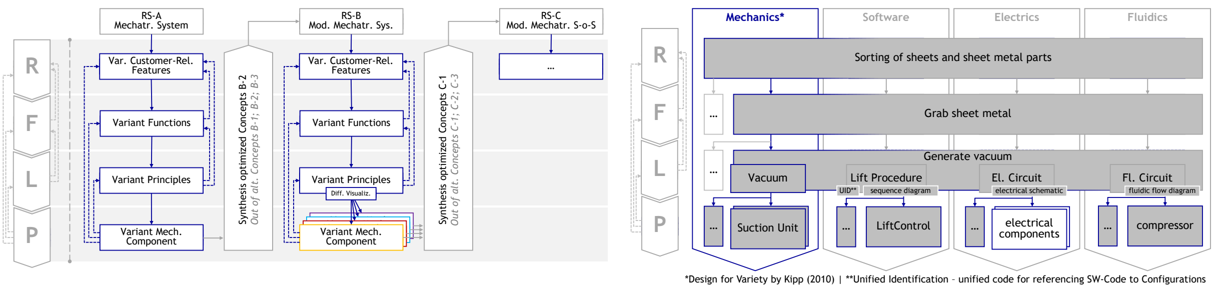

Figure 4. Cross-disciplinary adaption of the Design for Variety (x-DfV) method by Kipp (2010) (left); more detailed example of the case study (right).

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For the integration of several development disciplines likewise the "RFLP"-Approach is used as reference. It can be seen that the system architecture is linked to the physical architecture via the requirements, the functional and then the logical architecture (Eigner *et al.*, 2014). At the Physical Architecture level, the multi-disciplinary design process occurs in which the components are developed (Graessler *et al.*, 2018). It can be concluded that the integration of the discipline-specific components at the "P"-level into the Method of Design for Variety (DfV) creates a cross-disciplinary mapping and provides opportunity for harmonization. The integrated components are shown in Figure 4 on the left center in the context of the already mentioned Design for Variety context from Figure 2.
Figure 4 on the right shows a more detailed representation of the adapted method using the case study as an example. Here it can be seen that different disciplines are integrated in the consideration. On the first three levels "R", "F" and "L" the different disciplines have the same architecture and therefore the same relevant variant features, functions and logics. On the level of the logics, however, a specification has to be made. In the case of mechanical components, this logic can be represented by operating principles, such as "vacuum", but in the case of software, a somehow modified Adaption is necessary, since processes, i.e., dynamic behavior, are taken as a basis. For example, the process of lifting a plate. In the other disciplines which are part of the case study, electrical and fluidics, circuits are required. From this it can be concluded that the "L" level is shared but must be extended by different specifics. On the "P" level, the components are visualized analogously to the mechanical components. "LiftControl", for example, is implemented using variant programming, once with and once without parameterization, and "electrical components" is implemented using a variant number of circuits, but with standardized components, as for example a relay.

6. Systems-in-System as a Result of Cross-Disciplinary Modular Design

The result of the cross-disciplinary harmonization carried out on the example of the case study presented is a new modular product architecture which integrates the cross-disciplinary consideration in the variety-oriented design. In the new product architecture, the example shows a reduced interaction between the constituents and also a visible decentralization of processes across the entire product architecture. The resulting architecture can be placed in the context of the previously developed product architectures as a third level. A simple mechatronic system is the first level, on which all further considerations are based (Figure 5, left). If the simple mechatronic system is designed by Design for Variety and then modularized, the modular mechatronic system is created in the second stage (Figure 5, center). From this elaboration the third stage emerges, in which the modular mechatronic system is designed into a modular mechatronic systems-in-system (SiS) (Figure 5, right).

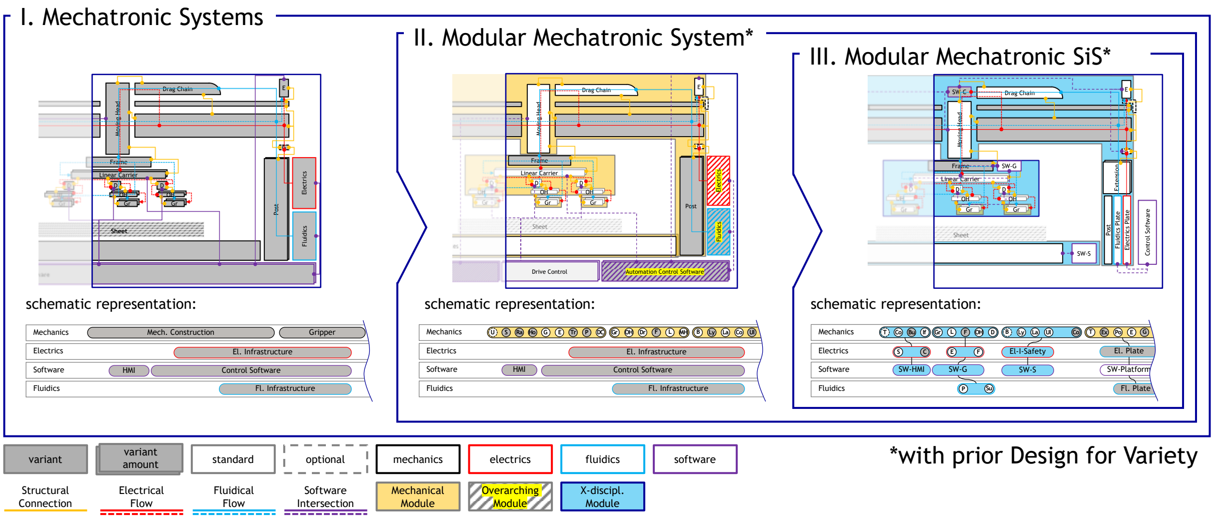

Figure 5. Three Stages of variety-oriented mechatronic systems, visualized by adapted Module Interface Graphs (MIG) (upper) and swimlane-based component levels (lower)

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The interactions and interconnections have been reduced throughout the three stages. As a result, the subsystems can operate almost "autonomously", but their joint interconnection enables the extensive functionality of the product. By decentralizing different discipline-specific components in cross-disciplinary structures, potentials can be generated in and beyond the life phase. In the life phase, for example, the repercussions between components of different disciplines can be better controlled. For example, a change in a mechanical component or an active principle has a reduced impact on the flow of the software, since this relates to a restricted part of the overall product architecture. Across life phases, subsequent individualizations are easier to implement in the field and in the after-sales or service life phase. A representative example of this would be the upgradeability of certain modules or the simple plug-and-play replacement of entire modules. Due to the decentralized components, it depends on the interface how the new module is integrated and not on the overall machine software.

7. Discussion

In this elaboration, the Design for Variety method by Kipp et al. (2010) has been applied to cross-disciplinary structures. It is important to note that the steps and method blocks performed here are not a substitute for the development of discipline-specific architectures and components, but only provides an additional way to extend and optimize the multi-disciplinary design process through a cross-disciplinary approach. In the example presented here, the ideas and aspects could be implemented well, as the project dealt with a simpler product architecture compared to other projects in the research environment. However, it should be noted that the integration of further perspectives and disciplines has significantly increased complexity. In this case study, the integration of further disciplines was not done in its entirety, as this was not feasible in a first step. However, in this work also an iterative procedure was addressed, in which the method of the Design for Variety can be set. Due to the placement in an iterative process, the elaborated state can be further refined. In addition to this, it should be noted that the state addressed here does not contain a fully harmonized module formation. As a result, however, non-harmonized subsystem boundaries can be viewed as a kind of platform since they represent the basic framework of loading and unloading automation. In the context of systems-of-systems, the representation still works. This is because the non-harmonized subsystems form a larger module that communicates with the other relatively self-sufficient modules and enables the overall function, see Figure 5. However, the potentials of maintainability and upgradeability, as well as plug-and-play replacement of such an extensive module are limited compared to smaller and autonomously functioning subsystems.

8. Outlook

This paper has shown that it is possible to integrate different perspectives into the approach of already existing methods of Design for Variety and Modular Design. However, the example of the case study listed here also shows that some aspects still need to be clarified and examined in more detail.

Thus, the interface of the additional development disciplines into the method steps of the Method of Design for Variety is to be examined and worked out. According to current findings by this study, this involves the different mappings at the "L" level. In addition to this, attention must be paid to ensure that there is a common knowledge base from which the different architectures are derived. For this, systems engineering can provide useful insights and tools to more accurately expose and map these linkages (Walden *et al.*, 2015; Morgan *et al.*, 2021). Additionally, there is a need to identify and research module drivers at discipline level and linkages between different disciplin-specific components. In this regard, Life Phase Modularization (Blees *et al.*, 2010; Krause and Gebhardt, 2018) provides a good reference model, but module drivers for cross-disciplinarity need to be located and applied within the life phase.

Another issue is the integration into an iterative or agile context. Integrating other perspectives increases complexity and decreases transparency, which was one main goal of the presented method. Iterative and agile approaches could improve the complexity of the method and re-emphasize transparency as an advantage on the other hand.

For the representation and evaluation of the presented method, the interactions of the cross-disciplinarity are to be explored and how these can be visually presented or even measured. The data

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basis can then be used for further validation and evaluation purposes on the observed architecture. To be able to fulfill such purposes, however, the previously mentioned aspects have to be further investigated.

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