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Multi-Disciplinary Product Design and Modularization – Concept Introduction of the Module Harmonization Chart (MHC)

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Abstract

Product systems no longer consist merely of discrete components that can be designed and developed independently. Instead, the product systems take on an increasingly complex shape, reflected in product architecture development. Various stakeholders in this product architecture must collaborate across life phases and disciplines to an increasing extent. To support the exchange in multi-disciplinary product systems in the context of modularization, the visualization tool of the "Module Harmonization Chart (MHC)" is presented in this paper. The "MHC" enables the representation of components in a multi-disciplinary system, thus supporting cross-disciplinary collaboration in developing an integrated modular design. Aspects such as discipline-specific module drivers and targeted sub-system segments can be used to address a holistic module design and improve overall system integration.

Keywords: modular design; product architecture; multi-disziplinary design; collaboration tool; design harmonization

1. Introduction

This paper introduces the Module Harmonization Chart (MHC) visualization tool. This visualization tool aims to support the collaboration of different disciplines as stakeholders in the development process of modular product families. Due to the increasing number of requirements, features, and functions a product system has to fulfill for the customer, the necessity for comprehensive integration of several development disciplines is continuously evolving [1,2].

Concerning software, as well as electronics/electrical engineering, in particular, the early and integrated view of the system form is gaining more importance for the development of the target system [3,4].

With the development of modular product families, there are already valid approaches to address the complexity of product system design. The decoupling and formation of modules result in additional difficulties considering different development disciplines, which are also affected by module scopes and specific interfaces [5,6].

The Module Harmonization Chart was developed to support this integrated view of modular product families in multi-disciplinary products. The visualization tool is intended to improve transparency and, thus, the collaboration of various stakeholders in the product system design process. In addition, it enables an improved integration of multi-disciplinary sub-systems or modules into the overall system by applying a harmonized design across participating disciplines.

In the following, underlying research and references are considered in section 2, and the identified deficit is shown in section 3. Afterwards, the Module Harmonization Chart is introduced in section 4 and further described and validated through an example in sections 5 and 6. In section 7, the current state of the tool is discussed, and further adaptations and objectives are considered in the outlook.

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Nomenclature

$V_{Comp.\ A}$	Variant Component A
$V_{Comp.\ A1}$	Variant Sub-Component A in Discipline 1
$S_{Comp.\ B}$	Standard Component B
$S_{Comp.\ B2}$	Standard Sub-Component B in Discipline 2
$X_{Comp.\ C}^{optional}$	Default optional Component (V or S)
$X_{Comp.\ C}^{multipl.}$	Default multiple Component (V or S)

2. Research Background

The limitation of this paper is the modularization of mechatronic systems in multi-disciplinary structures. This elaboration focuses on the product-sided consideration, whereas the collaboration of organizational structures is out of this paper's scope. To clarify the background of this work, on the one hand, the methodical development of product systems and, on the other hand, the methodical development of modular product families are discussed.

2.1. Methodical Product System Development

In the development of mechatronic and cyber-physical systems, various approaches support the consideration and integration of different stakeholders in the methodical development; in this research, development disciplines [2].

As an example of the methodical procedure, the V-model, according to VDI2206, is stated, which visualizes and circumscribes the system analysis, the discipline-specific designs, and then the system integration, including verification and validation. During system analysis, the underlying product system or corresponding sub-system is fragmented from the requirements to discipline-specific designs. This cascade enables the pervasiveness of the relevance of technical concepts based on the given requirements. Subsequently, discipline-specific designs allow the respective expertise of the individual development disciplines to be incorporated into the product system design to best implement the required design. The unique discipline-specific designs are then integrated into the overall system and cross-checked for the corresponding functions and requirements. The V-Modell thus provides a suitable framework for coordinating the collaboration and task distribution of different disciplines and planning them in the overall context [7,8]. The V-Modell is also adapted in systems engineering, a discipline that deals with developing complex systems, including mechatronic and cyber-physical systems [9,10]. Here, technical processes address the definition and design of the system architecture by involving all relevant stakeholders. There is a seamless link from the requirements to the unique designs and implementation. [9]

2.2. Methodical Development of Modular Product Design

As mentioned in the introduction, various valid approaches for developing modular product families exist for managing complexity. They all focus on dividing products by characteristics of modularization, like the decoupling of components, into sub-systems and/or modules. Additionally, combinatorics can be handled by suitable interface definitions [5]. A further aspect is structuring the architecture concerning variant-oriented design. The combination of variant-oriented design and modularization reduces the variant-induced complexity in the best possible way for modular product families and, thus, the design of an efficient product architecture [5]. There are various supporting methods for the consideration of variant-oriented product architecture. E.g., the *Design for Variety* offers an advantage in mapping and analyzing the variant product architecture by modeling different levels and allocations across the architecture. [11]

There is a diversity of approaches for systematic support for modularization of product architectures. Most approaches can be classified into technical-functional and product-strategic considerations. Technical-functional approaches are, for example, the *Design Structure Matrix (DSM)* [12], the *Functional Modularization* [13], and the *Heuristics, according to Stone* [14]. The *Life Phase Modularization* [15] and the *Modular Function Deployment* [16] can be mentioned for product-strategic approaches. Furthermore, there are also holistic approaches that combine the advantages of both approaches. These include, for example, the *Product Family Master Plan* [17] and the *Integrated PKT Approach* [5]. Considering multi-disciplinary system architectures and modularization, the selected approaches of van *Beek et al.* [18] and *Askhøj et al.* [19] are referred to.

3. Identified Research Deficit

In the research background, some aspects dealt with methodological support for developing complex systems, such as mechatronic and cyber-physical systems. Likewise, some aspects address the systematic design of modular product families. In addition, the Research Background also mentions approaches that explicitly apply modularization to mechatronic systems. Thereby, there are approaches of the technical-functional view, as well as the product-strategic and the integrated view. However, the research background shows no approach to modularizing multi-disciplinary product systems that also integrates the technical-functional and product-strategic view. Likewise, the complete integration of all stakeholders in the system design process is still missing.

The approach of *van Beek et al.* [18] shows a deficit in considering the collaboration of different disciplines as it focuses on the functional modeling of the integrated system. The MESA approach by *Askhøj et al.* [19] does not depict components that rely on different disciplines simultaneously, e.g., a pump depending on mechanics and fluidics.

Consequently, there is also a lack of suitable visualization to support the systematic design of modular product systems. Although some approaches, like the method of the DSM, can be extended by using MDMs and DMMs and adaptations for the targeted case [20], a suitable illustration for transparency and visualization is missing [21].

In conclusion, a visualization tool that supports the methodical development of complex modular mechatronic product families must be elaborated.

4. Module Harmonization Chart as Proposed Solution

The Module Harmonization Chart is presented in this section to support the modularization of multi-disciplinary product systems. It should be noted that the MHC is a visualization tool and not a method. The tool takes aspects from the research needed for improved collaboration and transparency. For the limitation of application, the *MHC* is classified as a comprehensive visualization tool of *Design for Variety* and *Life Phase Modularization* methods. Prior consideration of *Design for Variety* provides an already variety-improved product architecture, which can subsequently be transferred into a modular product architecture. Due to the integration of several stakeholders and the value-adding goal of harmonizing the product architecture for the overall company, the aspects of technical-functional and product-strategic modularization are relevant for consideration. Therefore, the *Life Phase Modularization* is relevant. The aim of the tool is to fulfill the requirement of being versatile and usable in many different application situations. Thus, the tool is designed to be used both as a visual and a matrix-based tool.

4.1. Identifying Stakeholders and Components

The *Module Harmonization Chart* considers the collaboration of development disciplines in multi-disciplinary product systems, meaning that the stakeholders will be identified and located in the Research & Development life phase. Compared to *Life Phase Modularization*, in which the stakeholders from *Module Process Chart (MPC)* are the individual life phases or the departments considered and involved, the *MHC* focuses on one specific life phase [15].

Analogous to the *MPC* from the *Life Phase Modularization*, attention must also be paid to the existing structures in the case of a request when selecting the stakeholders in the environment considered here. For further consideration, according to Zuefle et al. [21], the stakeholders are divided into the five representative disciplines of mechanics, electrics/electrical engineering, fluidics, control software, and firmware.

Figure 1 shows that the stakeholders are arranged in the rows in the *Module Harmonization Chart*. Components are arranged in columns according to the goal of assigning the stakeholders to them; this has several reasons:

- Better usability due to the higher number of components
- compared to involved development disciplines.
- The arrangement of the stakeholders among themselves corresponds to the representation of the parallel design process from the V-model mentioned in section 2 [10].

The components represented in the *Module Harmonization Chart* correspond to the product architecture components, which have been arranged before in the *Design for Variety* [11].

Since only variant components must be considered in the *Design for Variety*, the standard components are added to the *Module Harmonization Chart*. The prior Design for Variety does not have to be essential; however, it recommends taking a variant-improved architecture as the basis with the result that modularization can be accomplished more effectively.

In Figure 1, the components in the columns took over the notations of the product structure from the Design for Variety (circles above the component label). Thus, it is possible to regard the effects of the variance on the formation of the modules transparently.

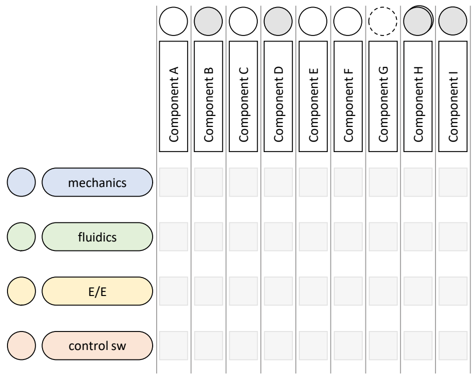

Fig 1. Arrangement of Stakeholders in MHC

Figure 2 also shows the *MHC* in two possible forms. Once in a visual form for workshop-based work in online collaboration tools or on-site, as well as spreadsheet-based.

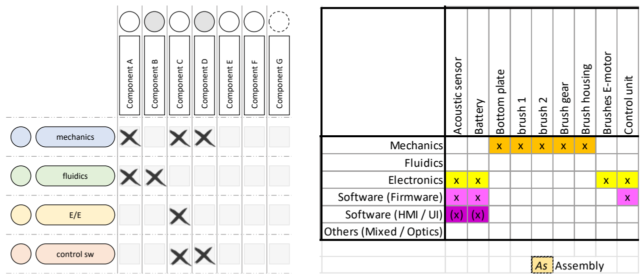

Fig 2. Workshop-oriented MHC (left) and spreadsheet-oriented MHC (right)

4.2. Allocating Stakeholders to Components

In contrast to *Life Phase Modularization* [15], the multi-disciplinary view of product architecture does not require that each stakeholder and, thus, each development discipline uses the same components. There are differences in the allocation of individual components depending on their origin and use. Examples, therefore, are mechanical components such as the wheel of a vacuum cleaning robot. However, it is also the case that electrotechnical components such as a sensor can be installed. According to the granularity of the preceding consideration of the *Design for Variety*, it is either two components with different disciplines or one component with two disciplines. Furthermore, the integrated components of software development can be added, which integrates immaterial components. The distinction between material and immaterial components creates a natural separation between hardware and software, but a conditional linkage of the components results.

In the *Module Harmonization Chart*, the components are assigned to the appropriate disciplines, which can be mapped and implemented exemplarily in a Domain Mapping Matrix (DMM) [21]. This results in the allocations between the stakeholders and the components. However, this binary mapping is further extended in the *Module Harmonization Chart* to provide a more detailed understanding of the designs. In the *MHC*, the notations of variance are also applied to the discipline-specific representation. Thus, the components can be classified separately in their variety on the level of the discipline-specific design. On the one hand, it supports further analysis of variety and, on the other hand, increases the understanding of interactions above all respective component stakeholders.

Variant components from the *Design for Variety* must contain at least one variant component on the discipline level (1). Conversely, standard components from the *Design for Variety* may only include standard components on the discipline level (2). This circumstance allows a first validation of the variance analysis across disciplines:

$$V_{Comp.\ A} = V_{Comp.\ A1} \wedge (S_{Comp.\ A2} \vee V_{Comp.\ A2}) \quad (1)$$

$$S_{Comp.\ B} = S_{Comp.\ B1} \wedge S_{Comp.\ B2} \quad (2)$$

The same applies to the components, which are determined as optional (3), (4), or variant quantity (multipl.) (5), (6):

$$V^{optional}_{Comp.\ C} = V^{optional}_{Comp.\ C1} \wedge (S^{optional}_{Comp.\ C2} \vee V^{optional}_{Comp.\ C2}) \quad (3)$$

$$S^{optional}_{Comp.\ C} = S^{optional}_{Comp.\ C1} \wedge S^{optional}_{Comp.\ C2} \quad (4)$$

$$V^{multipl.}_{Comp.\ C} = V^{multipl.}_{Comp.\ C1} \wedge (X_{Comp.\ C2} \vee X^{multipl.}_{Comp.\ C2}) \quad (5)$$

$$S^{multipl.}_{Comp.\ C} = S^{multipl.}_{Comp.\ C1} \wedge (S_{Comp.\ C2} \vee S^{multipl.}_{Comp.\ C2}) \quad (6)$$

Figure 3 illustrates the exemplary linking of the stakeholders with the components from the previous Design for Variety method. In addition, the linkage can be established spreadsheet-based by mapping a DMM or manually in a workshop by a writable MHC.

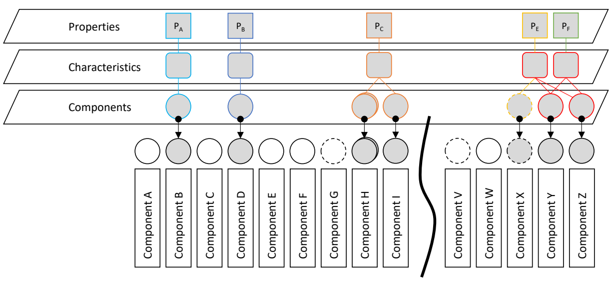

Fig 3. Transfer of component Level from Design for Variety into MHC

4.3. Evaluating Allocations between Components

For the usability and value-adding of the *Module Harmonization Chart*, the tool goes beyond the representation of a DMM. The elementary part of the MHC is to map the interactions between the stakeholders and the corresponding components. The interaction illustration refers to the characteristics of modularization, which describe the coupling, interface standardization, and functional connection between components and/or modules. The couplings are documented and extracted from the DSM and MDM as flows and interactions [21]. In a previous analysis by *Zuefle et al.* [22], it has already been suggested that module drivers can be considered and used in a diversified manner, in line with the goal of the architecture. Based on this concept, module drivers are used in the *MHC* to investigate discipline-specific designs. Since the existing product-strategic module drivers are too generic for the examined view, more specific module drivers must be used for the use case. In addition to the existing module drivers, according to *Erixon*, the use case maps non-functional requirements of the development disciplines [16],[22].

The selected module drivers are first quantified in an adapted utility analysis to transfer module drivers to the MHC in a differentiated manner. The adjusted utility analysis weights the module drivers in the overall context and assigns the module drivers to the components, depicted in Figure 4. Based on matrices, the DMM under consideration is additionally extended by the domain of the module drivers. It must be mentioned that it is not the evaluation of the module drivers to the components that determine the coupling but their weighting [21].

	Module Drivers	Relevance / Weight	Component A	Component B	Component C	Component D	Component E	Component F	Component G	etc.
mechanics	Module Driver A1	0,20	1	...	3	...	...	...	...	
	Module Driver A2	0,25	2	...	...	...	...	...	...	
E/E & fluidics	Module Driver A2	0,10	-	...	2	...	...	...	...	
	Module Driver A2	0,15	1	...	...	...	...	...	...	
software & firmware	Module Driver A2	0,05	-	...	2	...	...	...	...	
	Module Driver A2	0,10	-	...	1	...	...	...	...	
	etc.									
		1,00	0,85	...	1,00	...	...	...	...	

Fig 4. Relevance of Allocation by quantification of Module Drivers

The adapted utility analysis of the module drivers and the assignment to the components has a crucial advantage for the *MHC* by couplings being qualitatively quantifiable; thus, conclusions about the dependencies between components are made possible. This analysis supports, particularly in the context of modularization, in which the purposeful decoupling is aimed. The basic idea is that lower couplings by module drivers are better suited to create interfaces than couplings with a higher evaluation since the dependence is too large for creating interfaces [20],[23].

4.4. Harmonization of Sub-Systems

The *Module Harmonization Chart* aims to provide transparency and support for module formation in multi-disciplinary product systems. For this purpose, harmonized module concepts shall be created as an output of the visualization tool. The evaluation of the couplings between the subcomponents provides a way to decouple the components precisely. In a conceptual approach, harmonization was performed by prioritizing stakeholders [21]. Using the *MHC*, this prioritization is replaced by the utility analysis of module drivers, enabling a more objective modular architecture design.

However, to best implement harmonization, supplementary information must be considered in addition to 4.1 through 4.3.

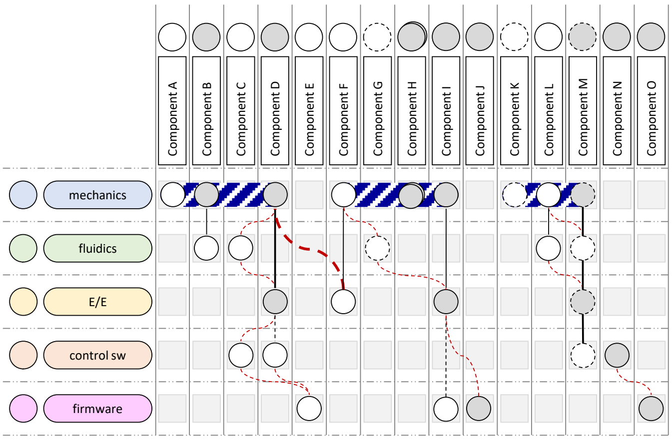

Fig 5. exemplary filled Module Harmonization Chart with Allocations

As described in the introduction of chapter 4, the *MHC* is supposed to be used as an additional tool between *Design for Variety* and *Life Phase Modularization*. Thus, the *MHC* can rely on already technically and functionally designed modules, which can be integrated into the mapping for better transparency (Figure 5, shaded blue). The representation enables transparency and a basis for discussing new and adapted module cuts, which would be more equitably designed in a cross- and multi-disciplinary harmonized context. For this purpose, the *MHC* shows action points in the design of cross- and multi-disciplinary module sections and gives incentives to rethink existing modules and harmonize them to an integrated context.

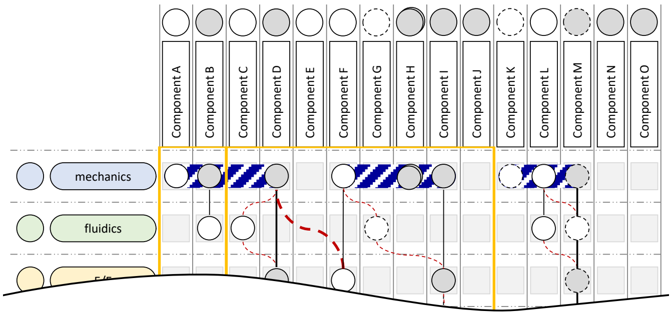

Fig 6. Exemplary alternative module Cut in MHC

Therefore, Figure 6 shows an exemplary illustration where the couplings between the components and the evaluation according to module drivers allow an alternative concept of module sections. Especially concerning an overall machine software system, this can have advantages since individual modules can be adapted to modules of other disciplines. Thus, maintenance, replacement, and extension can be simplified without touching other components in the modular product system.

5. Application of the Module Harmonization Chart

The presented *Module Harmonization Chart* is applied using the example of a robot vacuum cleaner. In doing so, the previous work of *Küchenhof et al.* [23] and *Zuefle et al.* [21], among others, was used to leverage *Design for Variety* – already performed – in a multi-disciplinary product system.

The example of a vacuum cleaner robot is also well suited for illustration, as its product architecture consists mainly of mechanical components and includes various electrotechnical and fluidic components. In addition, control technology software can also be considered in the example. For further information, it is referred to Küchenhof et al. [23]. The basis of the Module Harmonization Chart is derived from the available data and shown in Figure 7. The regarded development disciplines are listed in the rows, and the components of the variant-improved product architecture are listed in the columns. In the tabular representation itself, the sub-components of the discipline-specific designs are entered and connected vertically since they correspond to a parent component. In addition, modules are drawn in at the mechanical level by the underlying technical-functional modularization conducted in previous work [21, 23] (Figures 5 and 6, shaded blue).

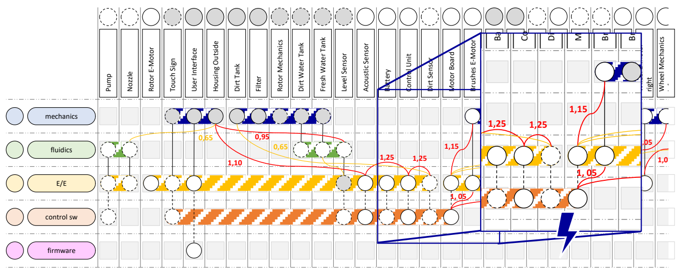

Fig 7. Module Harmonization Chart of Vacuum Cleaning Robot before Harmonization

In this example, Figure 7 shows that the discipline-specific designs are also modularized according to technical-functional aspects, which result in conceptual module selections. These discipline-specific modules have emerged from the survey of discipline representatives who have assigned components to each other based on their experience according to technical-functional aspects [21]. These module sections are harmonized, i.e., aligned, with the help of the MHC.

Among other things, the module drivers used for the representation are *Upgradeability*, *Transferability,* and *Exchangeability* [22]. *Due to the conducted utility analysis, exchangeability and the mechanical structure received the highest prioritization*. As seen in Figure 7, the weightings from the utility analysis were plotted in the *Module Harmonization Chart* and show various action points in which the discipline-specific module designs can negatively influence each other. By qualitatively quantifying the weights of couplings, issues for adjustment of the harmonized module intersections can be identified. As seen in Figure 7, there is no coupling between two of the orange modules, but they were put together in one. As a concept, the right-sided component is separated from the origin module and put into an isolated module located to the right-hand components. There are further action points for re-allocation along the mentioned one. All action points are discussed, and components are shifted due to the gained insights.

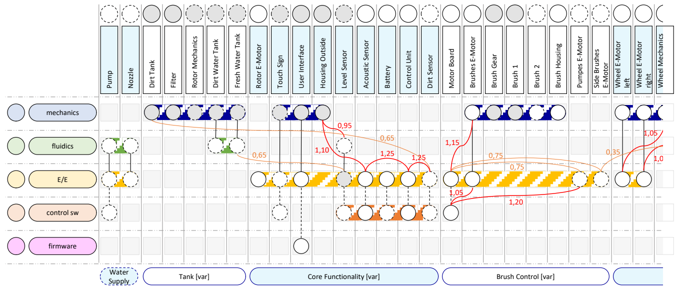

Fig 8. Harmonized Module Structures by Module Harmonization Chart

Figure 8 shows the harmonized module structure due to an expert workshop, which results from applying the *MHC*. The result shown is only one of several possible concepts. Depending on the stakeholders involved in the discussion, alternative solutions may emerge.

6. Discussion and Outlook

The presented tool works effectively in the examples to increase transparency in multi-disciplinary product systems and support the collaborative creation of modules. Even if the tool is not yet elaborated in its final maturity level, it already brings advantages in elaborating harmonized modular product system architectures. However, a few key points of the MHC must be detailed and refined in further research. For example, performing a utility analysis for prioritizing and quantifying module drivers is beneficial for evaluating the couplings. However, there is a lack of more in-depth studies and research on discipline-specific module drivers and their expression [22]. In the demonstrated use of the MHC, the connections between components were evaluated by their coupling. During the application, transparency of the product structure was increased with the result that it was possible to examine interfaces beyond the documentation in the DSM. In further investigation, it is also possible to regard the connections between the components and sub-components as interfaces and to generate statements based on it regarding the characteristics and organization of interfaces. On the one hand, this has advantages for module formation and maintenance of modules; on the other hand, it also benefits in structuring responsibilities around the interpretation of the interfaces between modules and in modules to define. However, this assumption requires further investigation, which will be initiated based on this paper.

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