Assessing the influence of digital innovations on the organizational design of product family generations

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Abstract: The paper discusses increasing demands on product architecture and the resulting requirements and implications for organizational structure. Due to the rising conditions, the product architecture is increasingly developing into a complex construct in which transparency must be increased to continue developing products effectively. The approach of this paper is, based on the method of Design for Variety, a matrix-based modularization with the DSM and its extension to a cross-discipline multi-domain matrix to establish a reference to the organizational structure and to align it in a value-added way to good product architecture. This is done by an exemplary Investigation of the product family generation of a vacuum robot.

Keywords: Modular design, Product family generations, Smart systems, Cross-disciplinarity, Multi-disciplinarity

1 Motivation & Introduction

In recent years, mechatronic products have increasingly developed into more complex mechatronic systems. This development is also necessary due to a wide variety of general conditions, such as the pressure for individualization or the desire for social interaction, but also technology-driven requirements, such as the expansion of certain product functions and additional digital components (Blecker and Abdelkafi, 2006; ElMaraghy et al., 2012; Kuhl et al., 2021). Conditioned by the increasing number of diverse requirements in the past, current, and future product family generations (PFG), this further evolutionary development means that many new structures, new components, and new processes need to be incorporated into the development of the product architecture. Product architecture is no longer primarily mechanical but is increasingly driven by elements from other development disciplines, such as electronics, fluidics, or software, in terms of firmware and human-machine interface (HMI), due to the integration of intelligent functions that such a product should provide (Tomiyama et al., 2019; Birk et al., 2021).

According to the mirroring hypothesis, organization and product architecture not only influence each other, but the organizational patterns of a development project (e.g., communication flows, geographic co-location, team and company assignments) adapt to those of the technical dependency patterns in the system under development (Colfer and Baldwin, 2016). Thus, the evolution, in combination with the Internet of Things, towards complex systems with global interaction leads not only to an increase of components in the product architecture but also to an increase in complexity due to the interaction of different components from different development disciplines (Hehenberger et al., 2016). This means that in a new PFG, complexity arises not only at the component variety level but also through their functional extension and increased interaction.

Accordingly, it must be analyzed to what extent the changes in the product architecture due to both increasing digital shares and the need for interactions can be transferred to the organizational structure, respectively to what time the transparency in the new product architecture can be mapped to such an extent that conclusions can be drawn about the organizational structure. For handling complex products and systems, the development of modular product families has become generally accepted (Krause et al., 2014; Küchenhof et al., 2022). The development of modular product families must be adapted to a discipline-spreading beginning to cover all interests of the involved development disciplines. A cross-disciplinary approach can help to provide a more transparent view of the interplay and interaction of different stakeholders in the development of a complex system, allowing conclusions to be drawn about the development of the organizational structure for future PFGs (Küchenhof et al., 2022).

In the following, selected approaches and methods of modular product family development and fundamentals of mechatronic system development are first presented in the research background. Based on this, a hypothesis is formulated in the methodological approach. Subsequently, a possible solution approach is presented. The solution approach is then explored and validated based on an exemplary object of investigation, the product architecture of a vacuum cleaner robot before the paper discusses the results and an outlook on further research steps.

2 Research Background

For further analysis of the problems presented in the introduction, the main aspects of developing mechatronic systems and modular product families are discussed in the research background.

2.1 Development of mechatronic Systems

Within this paper, the development of complex systems is equated with the development of mechatronic systems, as these require an increased interaction of different development disciplines, such as mechanics, electronics, and software. Other complex systems would also be the development of cyber-physical systems and the development of cybertronic elements (Küchenhof et al., 2022). In developing mechatronic systems, the V-model is often used as a framework for development, considered an example in this paper. The V-model helps to record the requirements and to form discipline-specific system designs on this basis. Subsequently, the discipline-specific designs are integrated into the overall system via the right-hand side of the V-Model and verified and validated via each integration status (Graessler et al., 2018; Birk et al., 2021).

Among other approaches, the V-Model uses the branch-and-bound (Morrison et al., 2016) and divide-and-conquer (Jin and Bettati, 2021) approaches, both of which divide a more complicated problem into subproblems to be able to solve the overall situation by solving the subproblems. In the context of mechatronic systems development, Eigner et al. (2014) place the V-model in the higher-level life cycle of the systems, from which the requirements for development come. These requirements are broken down via the V-model into functions, logic, and discipline-specific designs with discipline-specific components to more effectively implement the requirements (Graessler et al., 2018). The discipline-specific design phases form the basis for the architecture of the resulting system and thus also influence the development of a modular product family (Küchenhof Berschik 2022).

In Figure 1, the V-Model is shown in the context of the life phases of a system and extended by the designations of the different architectural levels from the Systems Engineering based RFLP approach (Requirements, Functional, Logical, Physical), which are requirements, functional and logical architecture, as well as physical structure (Eigner et al., 2014; Cadavid et al., 2021). In addition, the discipline-specific design phases are shown in the context of modular sections, which reflect the multi-disciplinarity in the V-Modell (Eppinger et al., 2014).

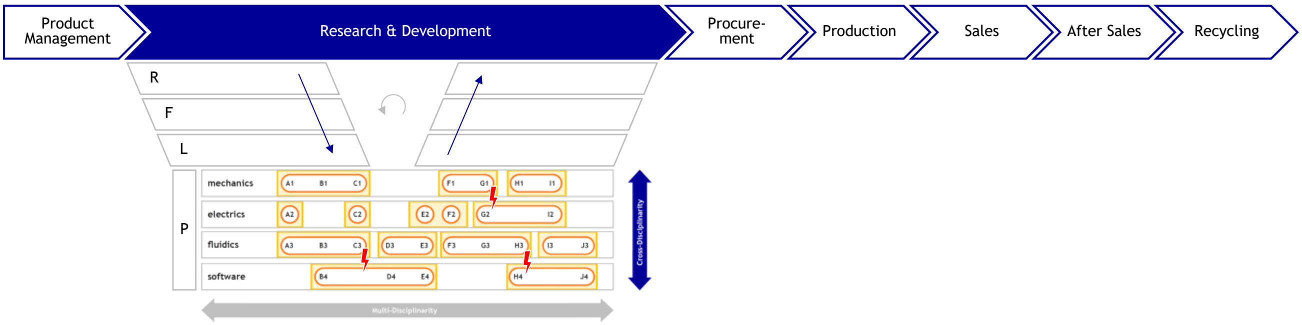

Figure 1. Multi- and cross-disciplinary design with the V-Model integrated into the life-phases of a product adapted from (Eigner et al., 2014; Küchenhof et al., 2022; Zuefle et al., 2021).

2.2 Development of modular Product families

Besides mechanics, the relevance of other development disciplines in developing complex mechatronic systems increases with each new PFG. Due to new parts and growing digital portions within the system, new interactions and challenges thus arise. To cope with the high complexity of such systems, the development of modular product families is one possible solution. (Krause et al., 2014)

Generally, the approaches and methods for developing modular product families can be divided based on technical-functional and product-strategic target considerations. As a product-strategic approach, the MFD, according to Erixon (1998), can be mentioned. For the technical-functional reference, the DSM and the functional modularization, according to Göpfert (1998), are exemplarily mentioned. There are also approaches in which both target considerations are integrated, such as the Product Family Master Plan (Simpson et al., 2012) or the integrated PKT-Approach (Krause et al., 2014).

The integrated PKT-approach is used to examine the cross-discipline product architecture discussed here since it provides a method with the Design for Variety (DfV), according to Kipp and Krause (2008), with which the product architecture can be analyzed for the relationship between an external and internal variety. In addition, the method maps the interactions in a Branch & Bound and Divide & Conquer-like manner across levels analogous to the RFLP approach. The method aims to ensure that, before modularization, the existing product architecture is first analyzed and designed to suit the necessary variety. The analyzed and identified interactions, mapped from the external to the internal variety, can thus be adapted to the goal accordingly. According to Kipp and Krause (2008), the method considers mainly the mechanical components that give a product its shape. However, some studies apply the DfV method to several development disciplines (Zuefle et al., 2022). Since the scope of consideration refers to the product architecture and the organizational structure in the research and development life phase, the life-phase modularization, according to Blees, which is included in the *Integrated PKT-Approach*, is not considered. As a substitute, the modularization method *Design Structure Matrix* (DSM) (Browning and

Yassine, 2016) is an example. The DSM is used in various application areas, including designing, analyzing, and structuring products, processes, and organizational tasks (Browning, 2016).

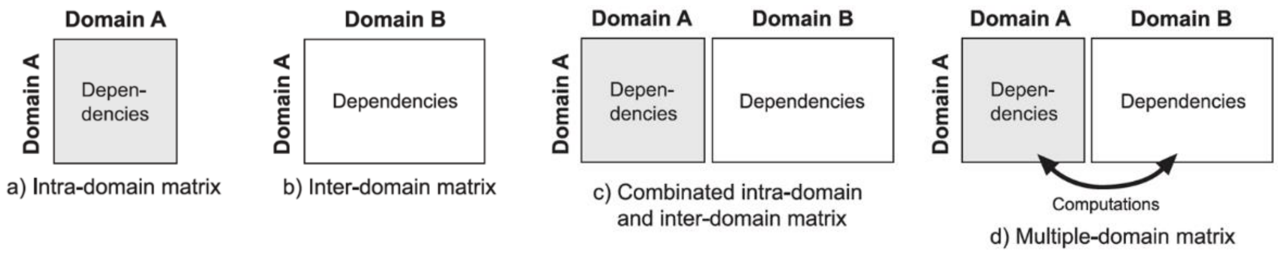

Figure 2. Classification of matrix-based approaches (Lindemann et al., 2009).

A DSM is a square intra-domain matrix representing system elements, such as product components, process steps, or organizational structures in the diagonal cells and couplings in the non-diagonal entries. Relationships and interactions between and within domains can further be analyzed in multi-domain matrices (MDM) (Eger et al., 2007; Browning and Yassine, 2016). Since this paper focuses on restructuring, a further look into the DSM literature leads to the ΔDSM and the change-DSM presented by De Weck (2007). The ΔDSM shows the difference between a base system and a changed system. Using system graphs, change-DSM can be used to show the change propagation paths of the considered system. Here, the initiating components are represented in the columns and the receiving elements as rows in the matrix, assigning a direction to the dependencies (De Weck, 2007). The concept of change- and ΔDSM is applied to the domains of DfV by Kipp and Krause (2008) method, which was transferred to matrix mapping in Küchenhof et al. (2020) for the development of a new PFG. The approach can support the planning of a new PFG by adding additional PFG-MDMs to represent the next generation (Küchenhof et al., 2019). The matrix view enables the linking of intra- and inter-domain relationships, such as product structure in terms of DSM and product architecture in terms of MDM (Küchenhof et al., 2020).

3 Methodical Procedure and Solution Approach

As introduced at the beginning, the growing demands on mechatronic products mean that interaction and collaboration between the development disciplines are gaining importance. Subsequently, a selection of DfV and modular design methods was introduced in the research background, which is considered exemplary in the following.

This paper discusses the hypothesis that the changes and influences on the product architecture, due to changed requirements and increased need for coordination in development, impact the organizational structure via PFGs and that an analysis of the product architecture can provide insights on the interaction with the organizational structure.

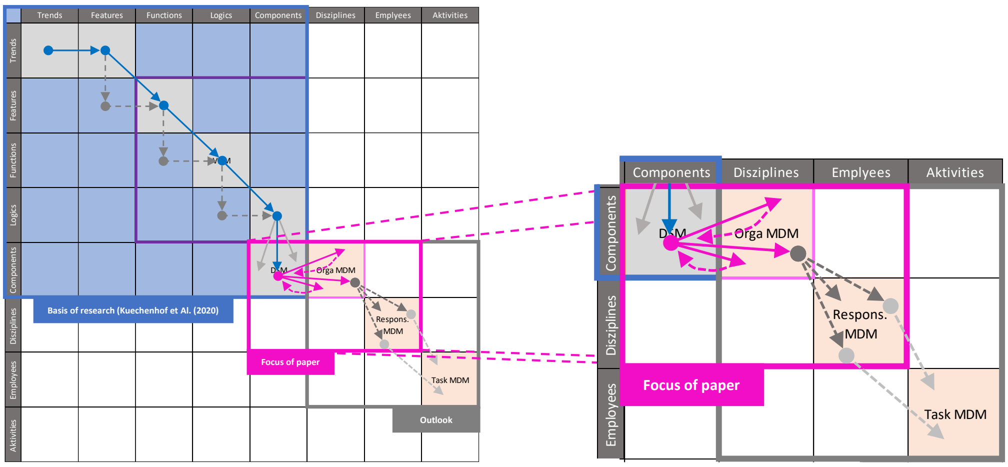

Figure 3. The topic and focus of this work are Küchenhof et al. (2020).

This hypothesis is analyzed and validated using a matrix-based representation in a definitive study. The matrix-based representation is chosen here because it can be easily extended to additional circumstances and additional considerations. As depicted in Figure 3, the work of Küchenhof et al. (2020) serves as the base for the analysis. The Integrated PKT-Approach presented has already been displayed in a matrix view. In addition, the handling of a product architecture has been demonstrated. Figure 3 visually illustrates the classification of the topic of this paper. The matrix-based integrated PKT-approach by Küchenhof et al. (2020) (highlighted in blue) forms the basis. It is extended as the focus of this paper to include the domain of development disciplines. This corresponds to the organization based on the DSM (highlighted in pink). In addition, the topic of the work is set in an expanded context with the integration of specific employees and individual tasks, which also represents the outlook for further goals (highlighted in gray).#

In this paper, the DSM of previously variant-oriented product architecture is extended to an MDM with the domain of the development disciplines. This is intended to represent the interactions and relationships between components and disciplines. In addition, the representation is supplemented in the context of the PFG by a function extension, whereby the solution approach can be additionally validated.

The solution approach examined here consists of the fact that the underlying product architecture is regarded as a black box, and for better investigation and illustration according to the approaches of the Branch & Bound or the Divide & Conquer into smaller components is broken up. For this study, the product architecture is separated into discipline-specific architectures per the objective. The discipline-specific architectures represent disciplines corresponding to a mechatronic system plus possibly other disciplines, depending on the subject under consideration. Figure 4 shows how the product architecture (grey box) is broken down into slices.

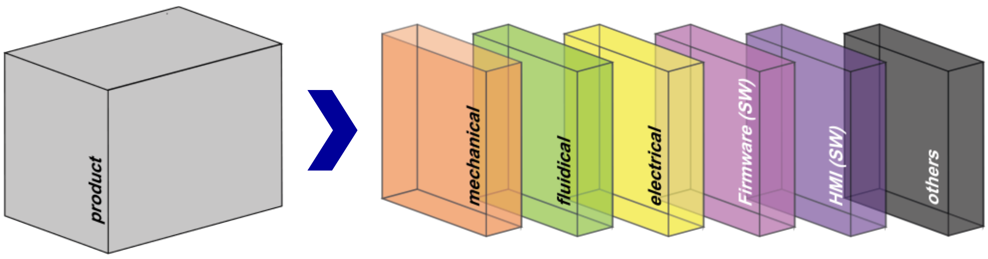

Figure 4. Separation of a product architecture into the individual discipline architectures.

Based on the work of Küchenhof et al. (2020), the Variety Allocation Model from the method of DfV according also serves as the basis for mapping the product architecture in this case. The model is well suited for the exemplary view since it represents the variant components, which also contain the idea in the DSM, extended by the standard components. If the approach of separating the discipline architectures from Figure 4 is transferred to the VAM, then divide the VAMs result for each development discipline considered (Figure 5 left to center). As part of the solution concept, this approach shows that the division into discipline-specific architectures also means that the interactions between the architectures must be considered. These are to be analyzed and made transparent accordingly with the MDM. As shown in Figure 5 on the right, the analysis of the unique architectures should result in added value in the integration of overall system architecture, compared to analysis and mapping as product architecture.

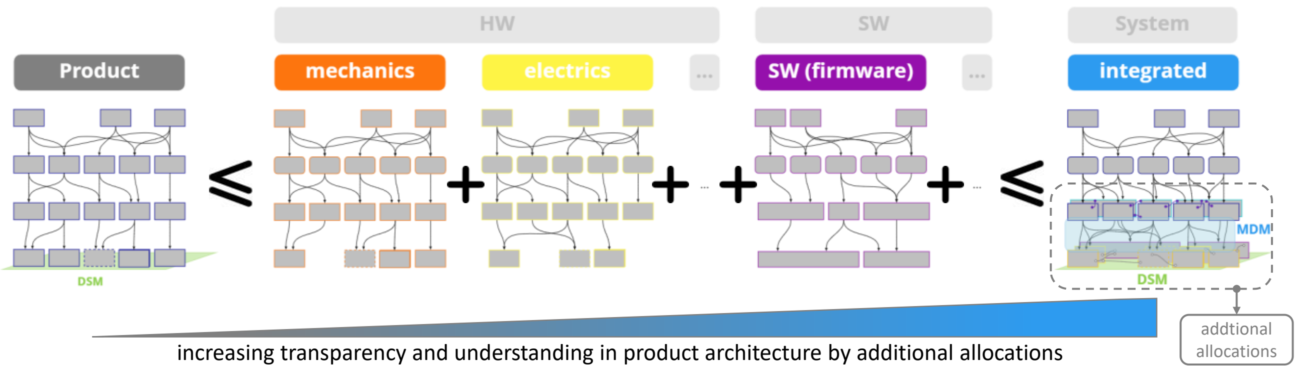

Figure 5. Derived architecture splitting on Variety Allocation Model in different discipline architectures with depicted goal and target of MDM and DSM.

For the execution of this investigation, an already variance-oriented product architecture in the form of a DSM is consulted. This is extended afterward to an MDM with the domain development discipline. In the MDM, which component is relevant for which discipline is documented. Based on the MDM, discipline-specific architectures are formed by selecting the appropriate components with discipline references. Thus, in addition to the couplings in the DSM, the responsibilities and relationships to development disciplines are also mapped.

According to the characteristics of the MDM, filtering by disciplines results in discipline-specific DSMs. These can be clustered into modules according to the DSM method. These discipline-specific modules are then harmonized across disciplines and serve as a template for possible organizational structures based on the harmonized modules. Further information on the product architecture is also available by correlating the components to the functions, further to the features and trends in Küchenhof et al. (2020).

In Küchenhof et al. (2020), dependencies from trends via features down to the component level, including mapping of the DSM and MDM, are already represented and elaborated in a matrix-based manner. This cascade of matrix-based mappings serves as the basis for further investigation. Thus, an analyzed and variant-oriented arranged product architecture is to base, which can further be considered in the following. In the established hypothesis, it is addressed that there are increasing interactions between the components of individual development disciplines in the product architecture of complex mechatronic systems. In addition, it is noted in the research background that in the context of the V-model, a multi-disciplinary view of the product structure of mechatronic systems is accomplished, in which on level of the components discipline-specific Design drafts are compiled. These results can be represented in interaction again in a cross-disciplinary VAM and thus directly as visualization of the variance-oriented product architecture.

4 Exemplary Application on Vacuum Cleaner Robot & Evaluation

The previously presented solution approach of extending the product architecture from the VAM and the DSM derived from it to an MDM with discipline affiliation of the components is analyzed using the right product family of a vacuum cleaner robot. The vacuum robot is an example that has already been designed and modularized, according to Gebhardt (2014). Accordingly, the benchmark offers an optimized product architecture as a basis and similar modularization concepts (Gebhardt, 2014). Figure 6 shows the vacuum robot's basic DSM, including the variance mapping on the diagonal, according to Küchenhof et al. (2020).

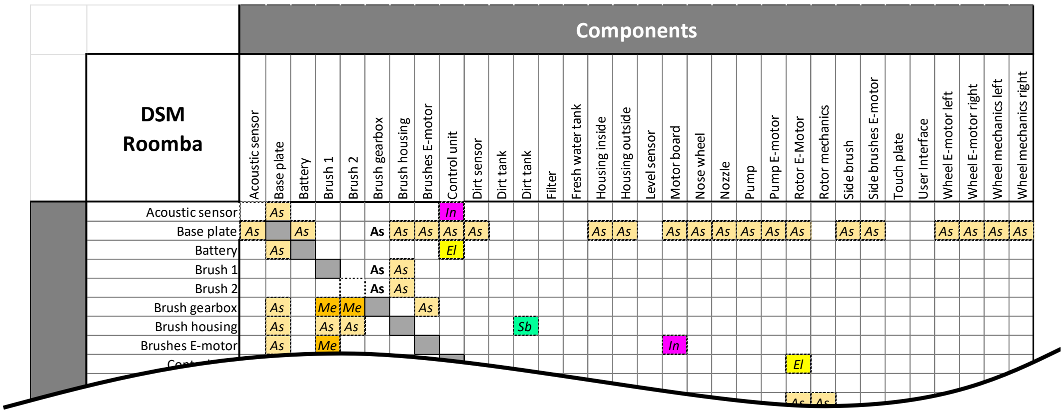

Figure 6. Basis DSM of exemplary Vacuum Robot.

4.1 Extended DSM by discipline-specific allocation

The DSM shown in Figure 6 was then extended to an MDM with the domain development discipline. The disciplines mechanics, electrics, fluidics, software (firmware), and software (HMI) were taken from Figure 4 and mapped. The colors of the representation were also adopted in the MDM. These colors enable a more intuitive differentiation between the disciplines in the MDM. The product architecture's components were assigned to the development disciplines in the next step. This corresponds to the possibility of setting several flows and couplings to an element, as used in the DSM. Multiple assignments can also be able to analyze components, which are dependent on different development disciplines, accordingly. Figure 7 shows a section of the MDM in which the components and disciplines are mapped to each other.

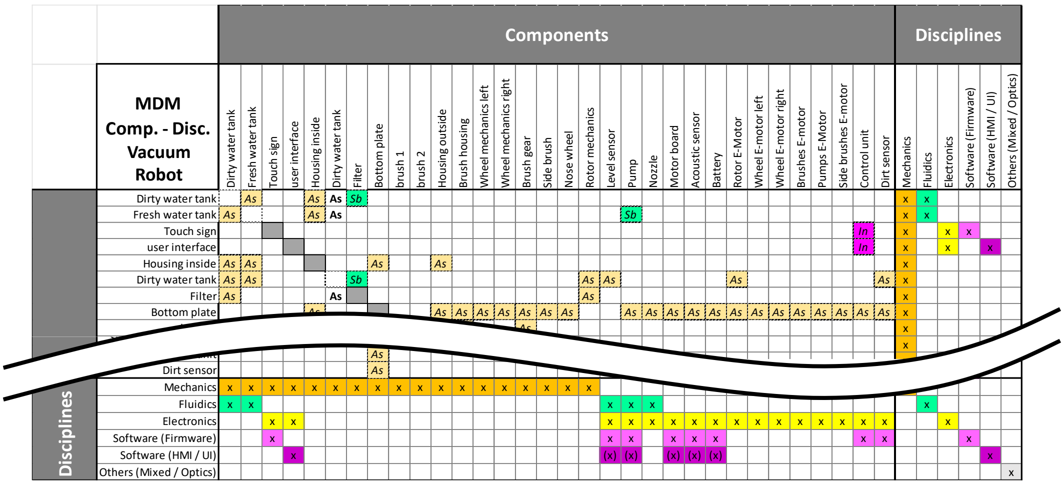

Figure 7. Example of the DSM of the vacuum cleaner robot extended to an MDM.

According to the affected disciplines, the components were filtered via the assignment in the MDM. This results in a separate reduced MDM for each development discipline, which still contains all the previously available information relating to the selection. The exciting aspect here is that not only one coupling remains mapped in the reduced DSM, but all coupling types continue to be mapped. In this example, there is only one coupling for each combination of components, so the DSM is not simplified. In other case examples, where a variety of two components involves multiple coupling types, the DSMs must be simplified beforehand and considered separately. Due to the paper's scope and the study example's capabilities, this step has been omitted here. Figure 8 shows a selection of discipline-specific MDMs, including DSMs.

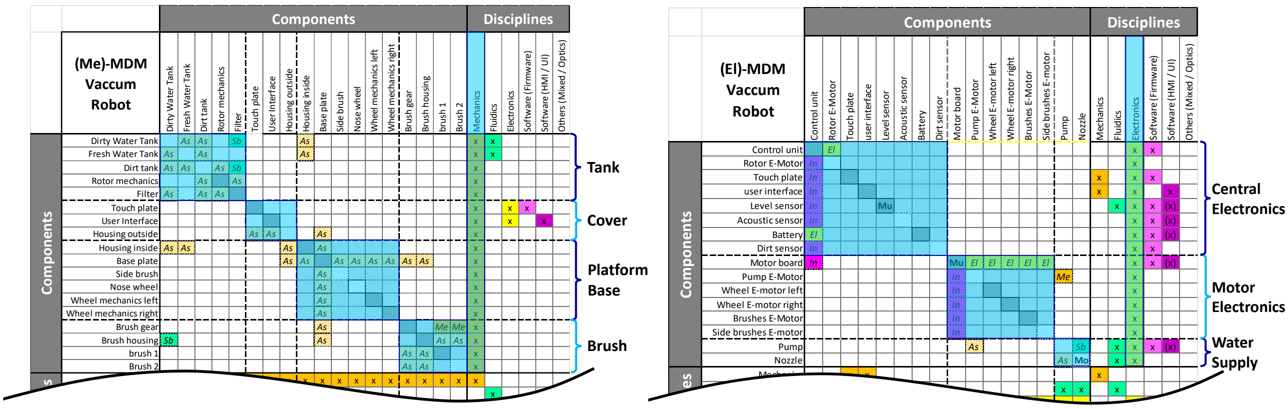

Figure 8. Sorted components in terms of their disciplinary assignment and influences (blue "modules" according to partial DSM; flows and structures map interactions of the components internally and externally).

As can be seen in the example of the mechanics DSM, there are three modules. On the one hand, there is the "brush" module at the bottom right, the "platform base" and "cover" module in the middle, and the "tank" module at the top left. By this modularization, the couplings mapped in the DSM can also be classified as module-internal and module-external couplings. In the example of the mechanical DSM just mentioned, the assembly couplings between the component "base plate" and "brush gear unit", as well as "brush housing", are to be mentioned. Thus, the interfaces between the modules can be identified. Conclusions about the organizational structure cannot yet be drawn comprehensively because the sub-DSM under consideration only represents mechanics as a development discipline for the time being. Accordingly, the other partial-DSMs must be integrated into the analysis.

As a further example, the electrics DSM can be considered in Figure 8 on the right - here, the sorting in the DSM results in the modules "central electronics", "motor electronics," and "water supply". For the entire partial DSMs, the modules shown in Figure 9 and their overlaps result.

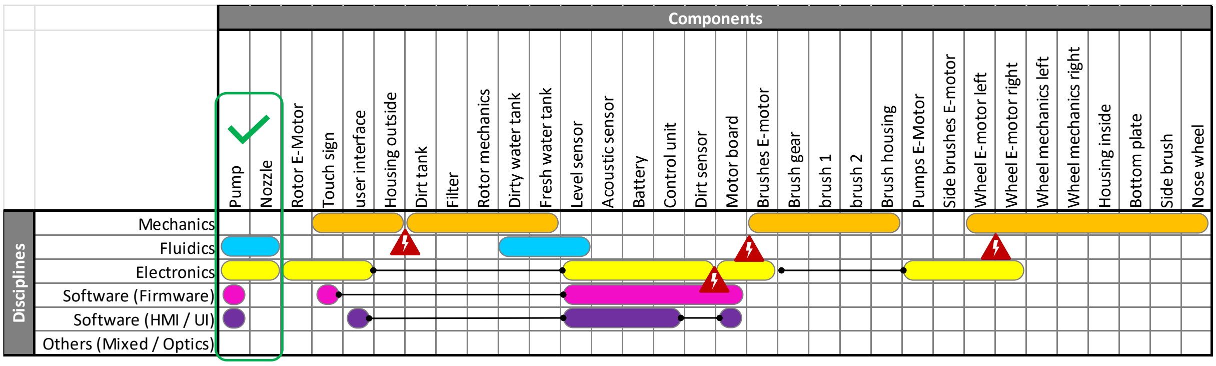

Figure 9. Exemplary approach of a Module Harmonization Chart (MHC) as an extension of a DMM resembling Zuefle et al. (2022).

Figure 9 and Figure 10 show the various module sections designed. In Figure 10, the module sections are visualized in the representation of the module interface graph as part of the design method for variety, according to Kipp and Krause (2008), which maps the component level of the product architecture. Both Figures show that the modules of the individual disciplines partially overlap and thus must be aligned in the next step in a modularization concept. As with simplified one-dimensional DSM, the alignment of the module sections corresponds to a compromise that must be validated subsequently.

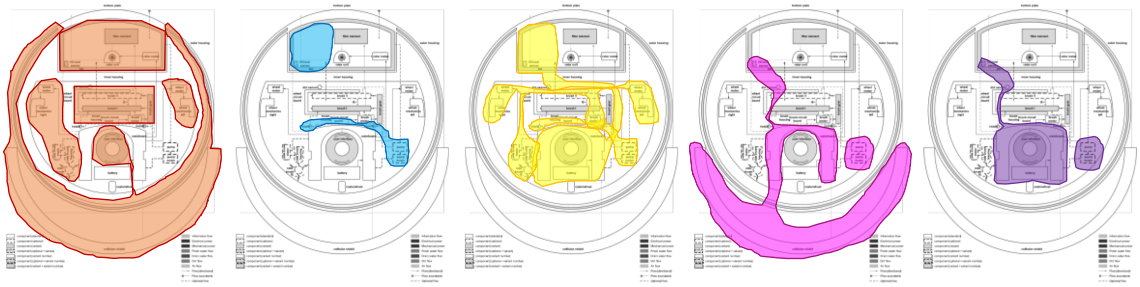

Figure 10. Discipline-specific module sections are mapped in the module interface graph (MIG) (Krause et al., 2014).

Due to the lack of validation possibilities by experts in the development of vacuum cleaner robots, the modules are harmonized according to a specific prioritization to achieve traceability. A possible harmonized result of the modularization based on the classification and assignment to development disciplines is shown in Figure 11. It should be noted that the harmonization can also be carried out in other ways and potentially result in deviating concepts.

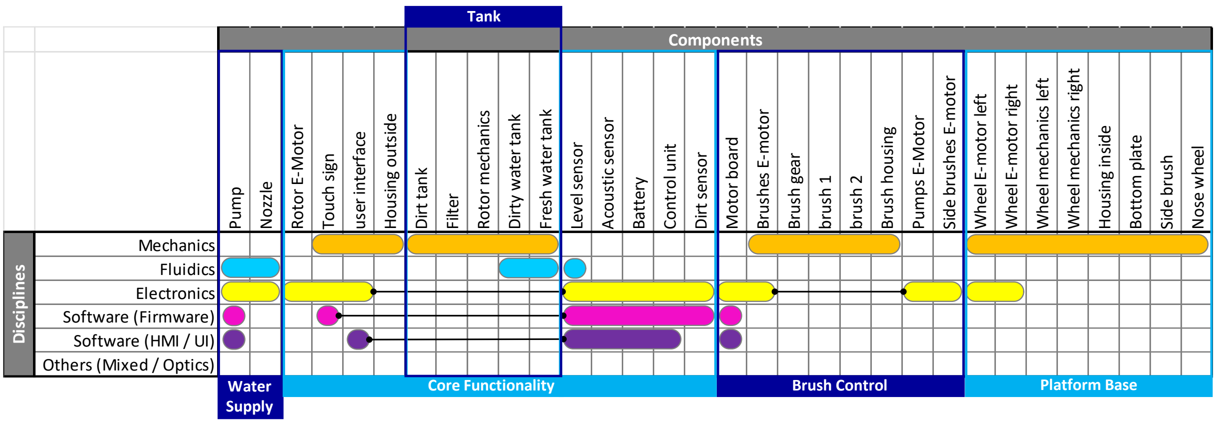

Figure 11. Harmonized modularization and team clusters allocated to different development disciplines and their allocation to the organizational structure.

This study serves as an exemplary representation of the procedure. In this example, the mechanical module formation is prioritized the highest, as far as the overall module sections are concerned, since the spatial dependency is highest for mechanical components, and the so-called "packaging" (Stadler et al., 2013) must be considered. Subsequently, the fluidic module formation and the electrical module formation are prioritized since the fluidic components are, according to the author's estimation, more critical in terms of installation space than the electrical components. Subsequently, the software module formations are considered, with the firmware being given priority over the HMI since the basic functionality depends on the firmware. This prioritization can be modified or redesigned accordingly to meet stakeholder demands.

Harmonized modularization enables cross-disciplinary teams to be formed whose organizational structure is based on the modularized product architecture, as shown in Figure 11. Compared to the modularization with the DSM without integrating the affiliation to disciplines, the MDM with allocating the components to the disciplines is more informative. Overlaps between organizationally separate areas can be identified based on the connections shown in Figure 9 (silo-driven thinking). The transparency gained can be used for harmonization and team building so that corresponding responsibilities and expertise can work together. It should be noted that there will still be overlaps, but these can be analyzed and reduced to a minimum, as shown in Figure 11.

4.2 Extended Functionality by new innovative components

As an additional example, the development of a new PFG with digital shares is analyzed. In the example shown here, the "filter" is further developed into a "smart filter" to enable the customer requirements of a possible adjustment of the filter and controlling the robot's motors. The additional and modified components "filter (smart-capable)", "filter vendor", a "mobile application (app)," and the adapted "control unit" result in additional interactions of development disciplines, also in the software area. Figure 12 shows the comparison of modularization according to the solution approach presented here with included discipline consideration (left) and modularization by the DSM without integration of the discipline reference (right).

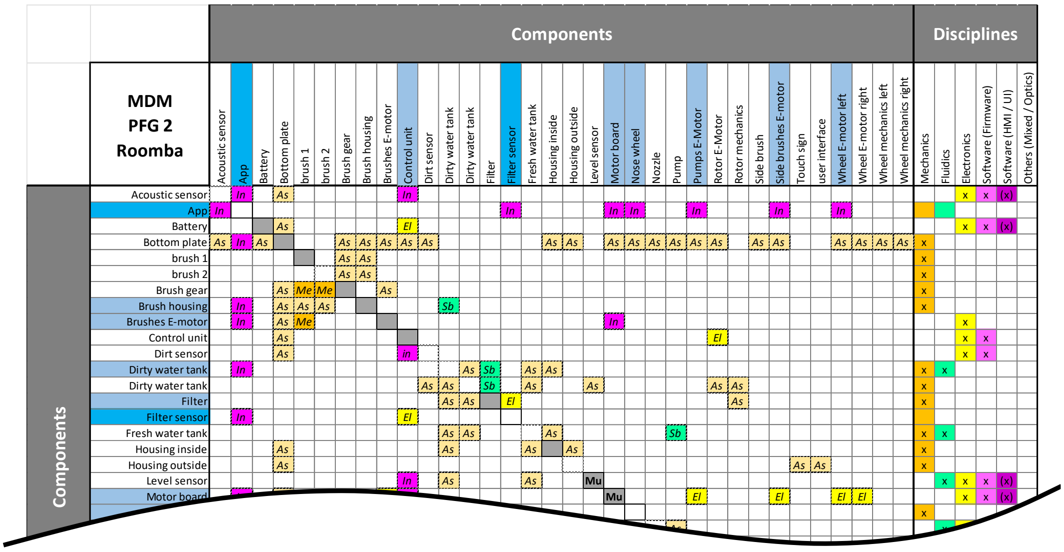

Figure 12. Updated DSM incl. "smart filter"-components highlighted in bright blue; all allocated parts highlighted in light blue.

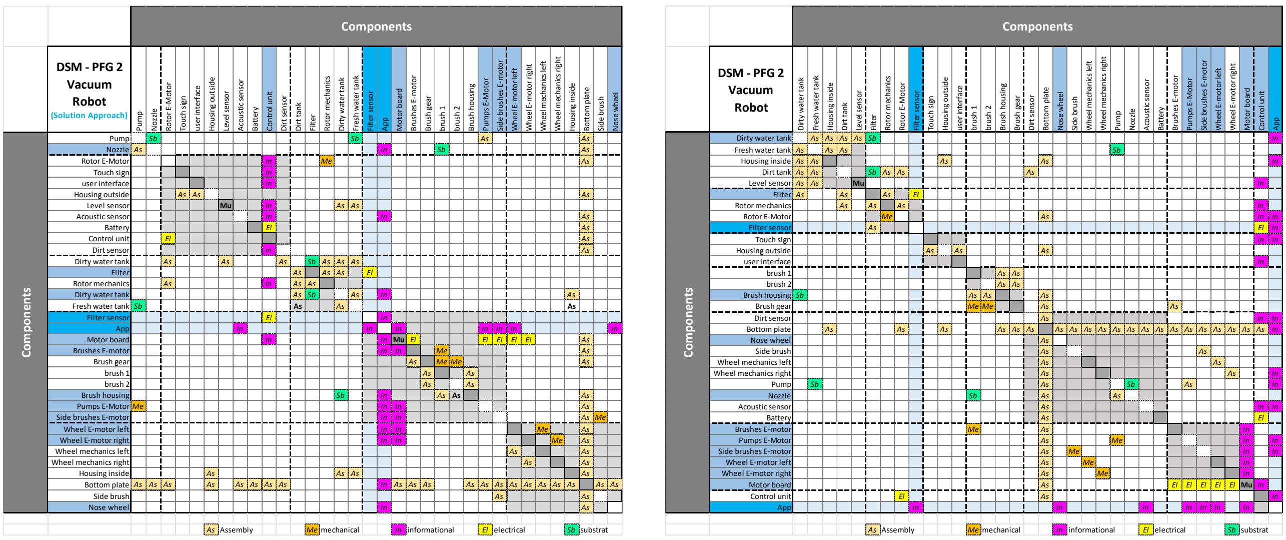

Figure 13. Sorted DSM with presented solution approach (left) and without discipline-specific allocation (right).

It can be seen that the allocation is carried out in a more informed way through the solution approach presented here, and at the same time, the added value can be generated not only for the product architecture but also for the organizational structure, which adapts to the new modular product architecture in the new PFG.

Compared to 4.1, the solution approach yields a slightly different result regarding the modularization of the HMI. This can be derived from the fact that the additional app is mainly HMI-related. The result is reflected in another cluster, which puts the app in a module with the motor board. Previously (in 4.1), the motor board was still in one module with the control unit and the sensors. Since the purpose of the application is to control the motors, the division makes sense. Since the motor board has already been separated from the control unit in Figure 11, this does not result in any new harmonization. The solution presented also results in fewer module sections (5 pcs) than in the example DSM (7 pcs) in Figure 13 on the right. This suggests that module cuts were merged and harmonized based on the organizational structure due to the team cuts. In addition, the solution on the right has a widely distributed allocation of digital shares, one of the issues mentioned in the beginning. It is assumed this is caused by the harmonization across the development disciplines and the allocation based on this. It should be noted that a different result is obtained depending on the premise that the harmonization is carried out.

5 Discussion & Outlook

The exemplary application of the solution approach has shown that it results in added value for the transparency and understanding of the system, which is becoming more complex, by extending it to include the disciplines and then modularizing it via the DSM. Similarly, by feeding back the insights from the MDM and discipline-specific DSM, there are benefits in using the VAM to represent the product architecture in the context of DfV. Only the component level in the VAM was considered and analyzed since here the most significant difference between the components and the development disciplines concerned are to be found; however, in further consideration also, the levels lying above, like the logical and the functional architecture, should be considered analogously, to make a value-added review possible in systems becoming more complex. The limited reflection on the component level results in a new way of looking at things between disciplines. This means that the correlation can no longer be mapped only between two levels (logical level and physical level in the VAM, but also in one group (here in the physical level distributed to different disciplines). In terms of organizational structure, value-added insights are also gained, as team sections can be derived analogously to module sections from the harmonized DSMs. This division counteracts silo-driven thinking and makes it possible for developers from different disciplines to work on a module in a targeted manner. The assignment of specific developers is potential via the extension of the matrices by the domain Employee or possibly Assignee, which was mentioned at the beginning. Thus, the organizational structure can adapt to the product architecture. However, it is to be considered that the product architecture can develop dynamically over different PFGs, and thus accordingly, the organization structure should create dynamically along. However, this conclusion is beyond the scope of this paper but needs to be considered further.

Further review of the cascade setup becomes interesting when the employee/assignee and process task domains are added. Thus, process tasks can also be integrated into the observation and harmonization in addition to product architecture and organizational structure. This is a component of further mapping implementations and research, whereby the domains product, people, and the process could be mapped according to 's (2021) matrix-based and in the context of the analysis of the product architecture. In addition, the approach presented here can also be transferred to a model-based approach regarding digitization using MBSE so that the data from the different disciplines can be better managed and support continuity and consistency. Information from the study example has already been mapped into Cameo Systems Modeler, which can be used for further consideration.

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