INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED23
24-28 JULY 2023, BORDEAUX, FRANCE

INCORPORATING FIELD EFFECTS INTO THE DESIGN OF MODULAR PRODUCT FAMILIES

Kuechenhof, Jan (1);
Berschik, Markus C. (1);
Beibl, Julia (1);
Alonso Fernández, Iñigo (2);
Otto, Kevin (3);
Krause, Dieter (1);
Isaksson, Ola (2)

1: Hamburg University of Technology;
2: Chalmers University of Technology;
3: University of Melbourne

ABSTRACT

With advancing digitalization, new technologies with more and more digital components make it necessary to integrate new components into current and future products. Sensors and actuators, such as motors, emit electromagnetic and thermal fields that can greatly affect product performance. Recent work has considered fields at the functional level using functional structures and at the system level using DSM. In this paper, the effects of fields on product architecture are investigated at the component level. Using an appropriate visualization, the impact of fields on the product structure is considered. Architectural guidelines are then used to develop suitable product structures. The methodological approach is then applied to a product family of vacuum cleaner robots. The overlaid field information helps to gain deeper insights into the product architecture. The approach is useful for representing alternative structures. The new mapping of functional and structural relationships by moving module boundaries against fields can help promote architectural innovation.

Keywords: Product families, Design for X (DfX), Design methods

Contact:
Kuechenhof, Jan
Hamburg University of Technology
Germany
jan.kuechenhof@tuhh.de

Cite this article: Kuechenhof, J., Berschik, M. C., Beibl, J., Alonso Fernández, I., Otto, K., Krause, D., Isaksson, O. (2023) 'Incorporating Field Effects into the Design of Modular Product Families', in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.228

1 INTRODUCTION

Modularity is a well-known approach to manage the design of complex systems to a planned architecture typically making use of targeted reusable modular subassemblies. This can allow for a more economical offering of multiple product variants and evolution over time. With advancing digitalization and the transition from classic mechanical products towards cyber-physical systems and Internet of Things with embedded intelligence, the level of complexity of these systems is also increasing (Hehenberger et al., 2016). Since new technologies often involve the integration of actuators or sensors, new challenges in developing products arise. Mechatronic components usually include electronic components and software for control or data measurement/ management purposes. These components generate at least electromagnetic fields, therefore considering field effects and their impact on products as well as their environment will be of great importance in product architecture design in the future.

Over recent times multiple separate methods for modular product design have been developed and used, from function structure methods (Stone et al., 2000), design structure matrix (DSM) methods (Browning, 2016; Sinha et al., 2019), and geometry-based module interface methods. All of these methods support modularizing new products through their internally incorporated heuristics. System architecture and modularity decisions are inherent to preliminary concept design. However, for comparing concept designs, visual representations can be helpful. Specific visualization of alternative modularization concepts of a product family can help present module interfaces and boundaries. Gebhardt et al. (2014) advanced the Module Interface Graph (MIG) to present alternative modular architecture boundaries on the product geometric layout. This is in contrast to function structures or DSMs which operate at a more schematic product description level.

In more recent work, Otto et al. (2020) support the modular design process considering field effects. Here, modules are considered for the difficult internal flows which are being insulated as fields and kept within the module boundary, and the useful flows conveyed by other fields into and out of the module. The approach highlights the necessary functionalities needed by a module such as field isolating components and other components capable of transforming and conveying the field flows. Otto et al. (2020) consider fields with function structure methods, and Sanaei et al. (2020) consider fields with DSMs. A further refinement to the field effects approach is the insight it provides on radical architectural innovations. Many radical innovations observed have been the movement of a product function across a field boundary, placing that function out of its previous field level into another. For example, the modern ship propulsor was enabled by moving the electric motor drive outside the pressure hull, or modern electric e-bike drives in which the electric motor was integrated into the moving wheel hub. Moving functions to a higher voltage operation, high temperature environment, or higher-pressure field are all examples. This insight enables directed innovation - finding means to move functions to different field levels.

This earlier work on fields and flows was developed using schematic function structures. However, at times with more matured product design activity there may already exist prototype subassemblies or preliminary layouts. In these situations, completely backing off to layout-free methods such as DSMs ignore available information. Here we develop the idea that field effects-based partitioning can be used not only for functional structure and DSM approaches, but also on geometric layout visualization such as the MIG.

In this paper, field effect guidelines and support for modularization concepts and design decisions are presented and applied to the visualization level of the product layout. The MIG is used as a structure to consider the location of fields on the layout (pressure fields, temperature fields, voltage fields, etc.) and alternative module boundaries, as well as the required boundary elements (seals, bearings, isolators, insulators, etc.) to isolate the field in the module. Further, we explore radical innovation through movement of functions across established modular field boundaries to further generate alternative preliminary design concepts. The approach is demonstrated on a mechatronic product family of robot vacuum cleaners, clearly highlighting the existing modularity approach of isolating kinematic motions into modules and interfacing them using electrical connections. Radical alternative design concepts are generated by considering isolating all electrical flows into a single module and using geared connection interfaces to motion modules.

2 RELATED WORK

Following Ulrich (1995), the product architecture is the scheme in which the functions of products are assigned to physical components. The difference between conventional product design and modular product design is that product architecture is traditionally the result of design activities, whereas in the latter case it is the input, as interfaces are defined at the beginning (Sanchez, 1996). We now review works on modularity related to field effects and innovation.

2.1 Functional structures and design structure matrix

Functions represent an explicit relationship of a technical system. They offer a mostly solution-neutral description between an input and an output variable (Verein Deutscher Ingenieure, 1993) and describe both, the purpose of a product and its behavior (Bender and Gericke, 2021). A product can be represented by the interaction of its different functions. Therefore, a hierarchical function structure can be used, where functions are divided into main functions, functions and sub-functions and thus offer the classification on the basis of which the later technical implementation can be built. Another way of structuring functions is the conversion-oriented function structure. In this structure, the functions are linked to each other to resemble inputs, outputs and their different conversions. The represented functions or states are interconnected by energy, material or information flows (Ehrlenspiel and Meerkamm, 2013).

Function-means models are a way to specify an architecture with a hierarchical structure (Schachinger and Johannesson, 2000). Modelling the product structure of decomposable products in this way is a top-down process that is performed simultaneously in the functional and physical domains, as in axiomatic design. An enhanced function-means (EF-M) model capable of representing the constraints of the design space as well as alternative designs can be used as a basis for the development of a new product variants (Müller et al., 2019). The interactions between design solutions in an EF-M model can be extracted into a DSM. The use of function structures in modularity and product architectural analysis was pioneered by Stone and Wood (2000). Guidelines are provided on identifying modules as clusters of functions in the function structure. These are extended to modular product families using function structures (Otto and Zamirowski 1999). Such modularity schemes remain at the functional level of abstraction.

Another possibility to depict technical systems is the DSM. It shows the coupling of different components in terms of their spatial, energetic, informational or material relation (Steward 1981, Pimmler and Eppinger 1994). The entries within a DSM matrix denote the couplings that result from the pairwise consideration of all components, as such it should be apparent a DSM is simply the adjacency matrix of the graph of flows between components as above for a functional view. DSM offer the possibility of use with computer-aided calculations for large systems. As the couplings of the components are transferred into concepts for modularization the components are clustered to create a modularization concept (Pimmler and Eppinger 1994). Consideration of product families with DSM was considered among others by Blackenfeldt (2001) and Williamson and Sellgren (2016) looking for shared modules by combining modular function deployment methods (Ericsson and Erixon 1999) with DSM.

2.2 Incorporating field effects with functional structures

Otto et al. (2020) present guidelines to incorporate field effects in the product development process, which are listed in table 1. In general, the guidelines help the designer to identify fields and components sensitive to those fields to define the module boundaries and find innovative solutions. The term field is defined from the perspective of engineering mathematics, as a "scalar or vector physical quantity with each point in space which influences the materials and physics of a system" (Otto et al., 2020). This definition also includes field effects related to kinematics. Otto et al. (2020) distinguish necessary fields which provide the desired function and undesired ones which potentially harm other components. In order to avoid the need for field isolating components, guidelines help to draw module boundaries. They aim at using synergies of opposite fields and moving field sensitive components away from harmful fields across existing module boundaries (Otto et al. 2020). Function structures are used as visual support for the application of the guidelines.

Table 1: Summarized list of guidelines presented in Otto et al. (2020).

Guideline	**Explanation**
Guideline 1	Modules should be separated at field boundaries.
Guideline 2	A maximum-sized module should be defined by the zone boundaries required by kinematic, electromagnetic, thermal, or other fields.
Guideline 3	For parts, components, or functions with force bearing interfaces, consider moving an element further inside or outside the module boundary.
Guideline 4	For a kinematic joint (flow of kinematic motion or its conjugate) between two modules (components or functions), consider moving the two adjacent parts further within either module.
Guideline 5	For any electrical, temperature, or other field boundary of a module, consider moving a part (component or function) across the boundary and out of the module.
Guideline 6	Consider locating heat-sensitive modules outside the heat path zone.
Guideline 7	Fluids can leak, so consider placing liquid sensitive modules above potentially leaky modules.
Guideline 8	Consider placing modules to use the direction of the desired field flow and not against it.

2.3 Incorporating field effects with design structure matrices

In comparison to conventional DSM approaches which cluster components according to their connectivity, Sanaei et al. (2016) consider constraints in the modularization process and particularly investigate the influence of field effect constraints on the product architecture. The approach introduced by Sanaei et al. (2016) enables the designer to interactively apply constraints during the modularization with DSM.

Sanaei et al. (2016) include three alternative interactive algorithms with slightly varying procedures. For the identification of those constraints and the evaluation of suggested module clusters the designer can start with a functional structure graph. The designer starts with the pre-specification of the interfaces of the product which have to be split up or kept. Based on the input the algorithm suggests a modular architecture that the designer adjusts according to constraints regarding components' sensitivity to field effects. An iterative loop starts until the designer evaluates the suggested architecture as the optimal solution for the modularization task (Sanaei et al. 2016). A second algorithm starts with two different modular architectures from which the designer is asked to choose one. Then improved architectures with further hierarchical clusters are computed and presented and the designer again selects one and marks the relations which violate constraints. This step will be repeated until a solution is found (Sanaei et al. 2016). A third alternative interactive algorithm provides three different modular architectures at the beginning and the designer is required to choose one of them and mark connections which violate constraints. The information is processed and the interaction loop continues with the suggestion of an improved architecture until the designer's constraints are satisfied (Sanaei et al. 2016).

2.4 Product family development and conceptualization with module interface graph

The Integrated PKT-approach is focused on modular product families, to satisfy an external variety with low internal complexity (Krause and Gebhardt, 2023). It contains the two methods of Design for Variety (DfV, see Figure 1) and a technical-functional and product-strategic Life Phase Modularization after. In DfV different levels of abstraction are considered, from functional to form. Functions of the product family under development are treated in a functional structure. On the other hand, the structure of the product family in terms of components, interfaces and the variety of both are displayed in a component level MIG. The modularity guidelines from Stone et al. (1999) can be used on the functional level, and the mechanical layout of these modules is considered in the MIG (Küchenhof et al., 2019). The MIG approach is useful for considering component layouts along with the modularity partitioning alternatives regarded at the function structure level. We seek here to now expand on these works and incorporate field boundaries from the function structure and DSM works on component layouts using the MIG approach.

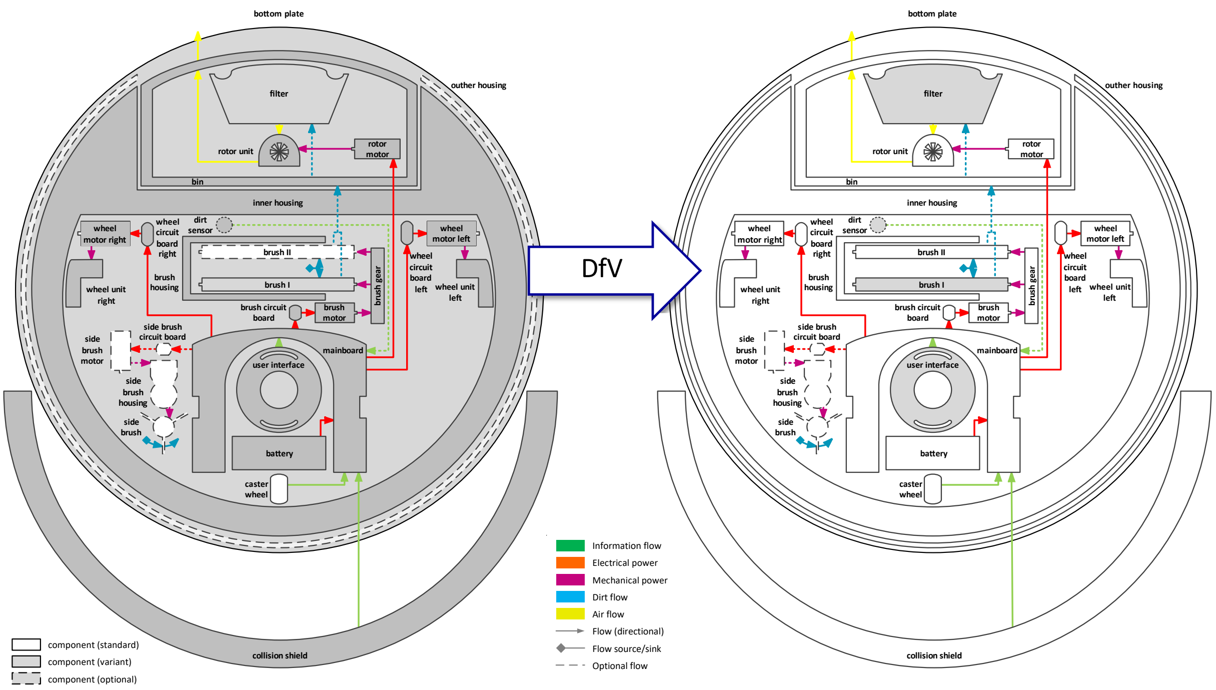


Figure 1: Baseline current product architecture of vacuum cleaner robot as viewed on a MIG before (left) and after (right) Design for Variety (DfV) with increased number of standard components (Gebhardt et al., 2014).

2.5 Innovation and modularity

Following Otto et al. (2020) we also seek to explore the use of field boundary changes against module boundaries to consider new innovative modular designs. On the definition of innovation in the context of modularity Henderson and Clark (1990) built on the categorization of incremental and radical innovations by examining the product architecture in terms of its components and their interconnections. The different types of innovation are classified along two dimensions, as shown in Figure 2 on the left.

		Core Concept	
		reinforced	overturned
Link between core competence and components	unchanged	Incremental Innovation (a)	Modular Innovation (b)
	changed	Architectural Innovation (c1, c2)	Radical Innovation

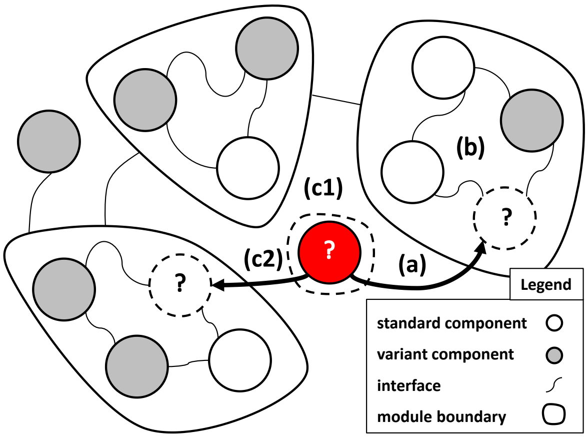


Figure 2: Left: Innovation framework after Clark and Henderson (1996); Right: Exemplary modular product structure considering the different types of innovation (Küchenhof et al., 2020).

The horizontal dimension shows the impact of the innovation on the components and the vertical axis shows the impact on the links between them. Incremental innovations introduce small technological changes to an existing product (a), mostly improving specific components and embedded functions. Innovations that change the core concept of a technology can be understood as modular innovations (b), where the relationships between the modules remain the same. The reconfiguration of an established system, linking existing components in new ways, is called an architectural innovation (c1, c2), often triggered by a change in a component. In Küchenhof et al. (2020) the impact of modularity decisions during initial product architecture development is assessed by a product reasoning framework which can be used to estimate the product's overall value and market performance.

3 GUIDELINES APPLICATION ON MIG

For modularization, the MIG after variant-oriented design is used (Krause and Gebhardt, 2023). We consider here a product family of vacuum cleaner robots. The MIG of the vacuum cleaner robot is shown in Figure 1. After DfV a modular structure can be developed.

What can be seen is the current architecture has isolated all kinematic motion components into modules. All motors, bearings, shafts and wheels are contained in motion modules. The flows crossing module boundaries are all electric contacts or wires. This is even true for the air movement vacuum suction modules, where the drive fan is part of the suction module, with again an electric contact and sensor wire crossing the module boundary. Similarly, all connections to the controller module are using electrical contacts. The same is true for the battery module. Electrical connections are the inter-module interfaces, and all other flows are insulated within modules.

Consideration of alternative means other than electrical connections as interfaces between modules offers new opportunities for radical improvement of the architecture regarding various criteria. For example, none of the modules are easily recyclable, all modules contain many different materials which must be disassembled to be recycled as separated materials. Many such different ideas are possible, simply by considering moving the module boundaries. We now analyse that systematically.

The architectural guidelines presented in Section 2.1. for consideration of field effects are now applied to the MIG, which represents the product structure of the robot vacuum cleaner product family. In doing so, we proceed in five main steps which are pictured in Figure 3.

Figure 3: Procedure for developing structural alternatives considering field effects.

First, we need to identify the different fields and then apply the guidelines presented in Table 1. Once a field has been identified, the associated color can be used to visualize the field and its range within the MIG. The third step is to consider structural alternatives by moving components, assigning them to new modules, changing interfaces, or defining new interfaces using the guidelines on component level. Modules are formed under consideration of the interaction of fields and components, trying to find a reasonable arrangement. The goal here is to avoid harmful combinations of field effects and field-sensitive components and to promote the most synergistic fulfilment of the defined product functions. Subsequently, the structural alternatives and the associated change in the functional performance of the components and modules can be evaluated using Clark and Henderson's innovation framework or in terms of product value and market performance according to Küchenhof et al. (2020). Finally, a final product layout is created that takes into account the trade-offs among the various alternatives. The concept can then be designed and a prototype built, e. g., through additive manufacturing.

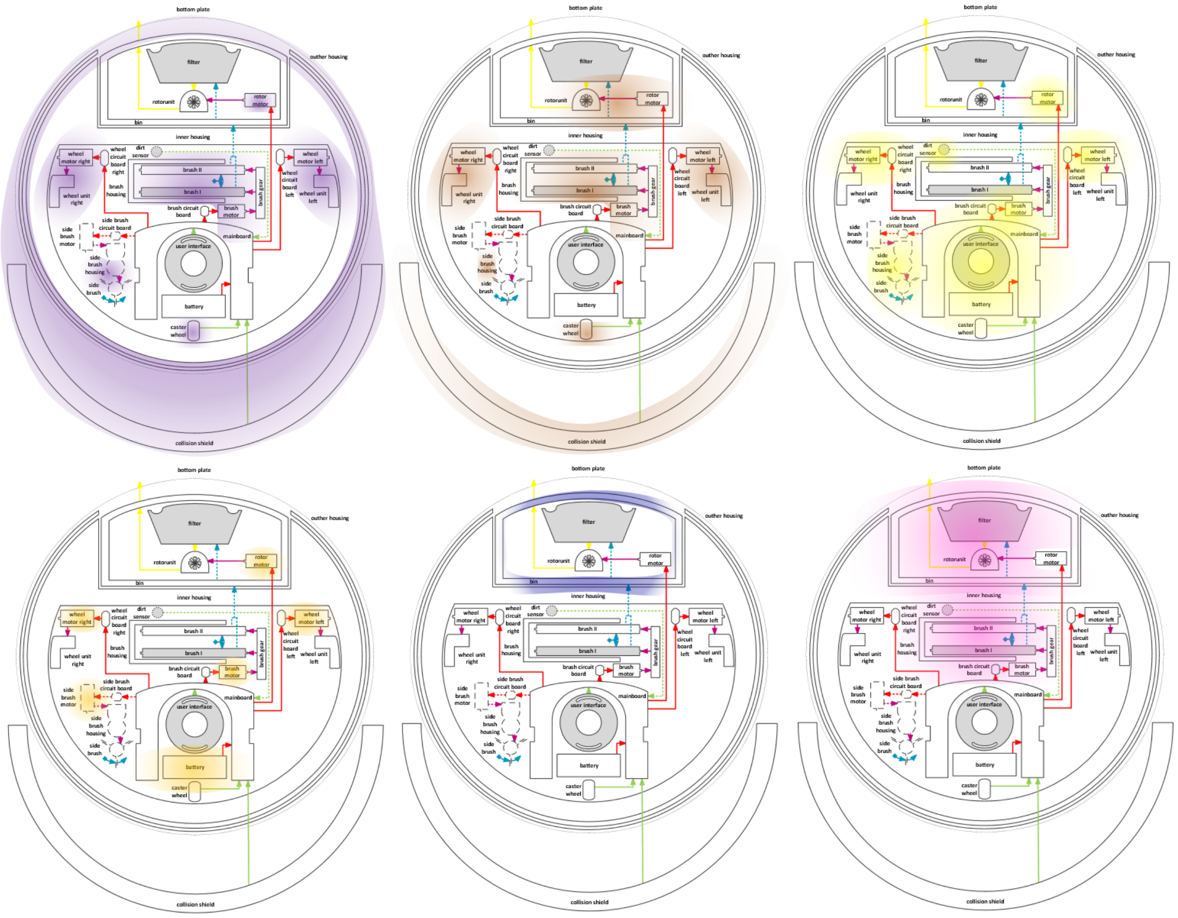
3.1 Identification and visualization

The first two steps shown in Figure 3 for identifying fields and visualizing them are performed iteratively until a satisfactory and consistent result is obtained. The identification process is explained below using the robot vacuum cleaner as a product example; the visualization results are shown in Figure 4.

Force: For architectural guideline 3 (Force), all components that absorb forces are identified. In the MIG, these are marked in purple. An aid is the consideration of the mechanical flows that connect components. Thus, components where mechanical flows pass through hence absorb forces. Regarding large forces flowing across module interfaces, the dust bin module interface to the air and dirt movement module stand out. As shown on the MIG, this requires a high force sealed interface, so the collected dust and air are transferred over to the dust bin. An alternative is to integrate the brushes into the dust bin, thereby keeping the high forces contained within the module consisting of dust bin, brushes and fan. The brushes and fan could be driven by a gear pair with the electric motors not being part of the module.

Kinematic Joints: For architectural guideline 4 (Kinematic joints), all components that move are identified and marked. In our example, this includes wheels, motors and brushes and associated gears.

In marking these kinematic field boundaries, it is apparent they already exactly align with the existing module boundaries. As can be seen on the MIG, motions do not cross module boundaries but are contained within wheel modules or the brush module. Kinematic motion field isolation is apparently a module driver in the current architecture.



Field	Force	Kinematic joints	Electrical	Heat	Gravity	Pressure
Field Color	🟪	🟫	🟨	🟧	🟦	🟪

Figure 4: MIGs and identified fields.

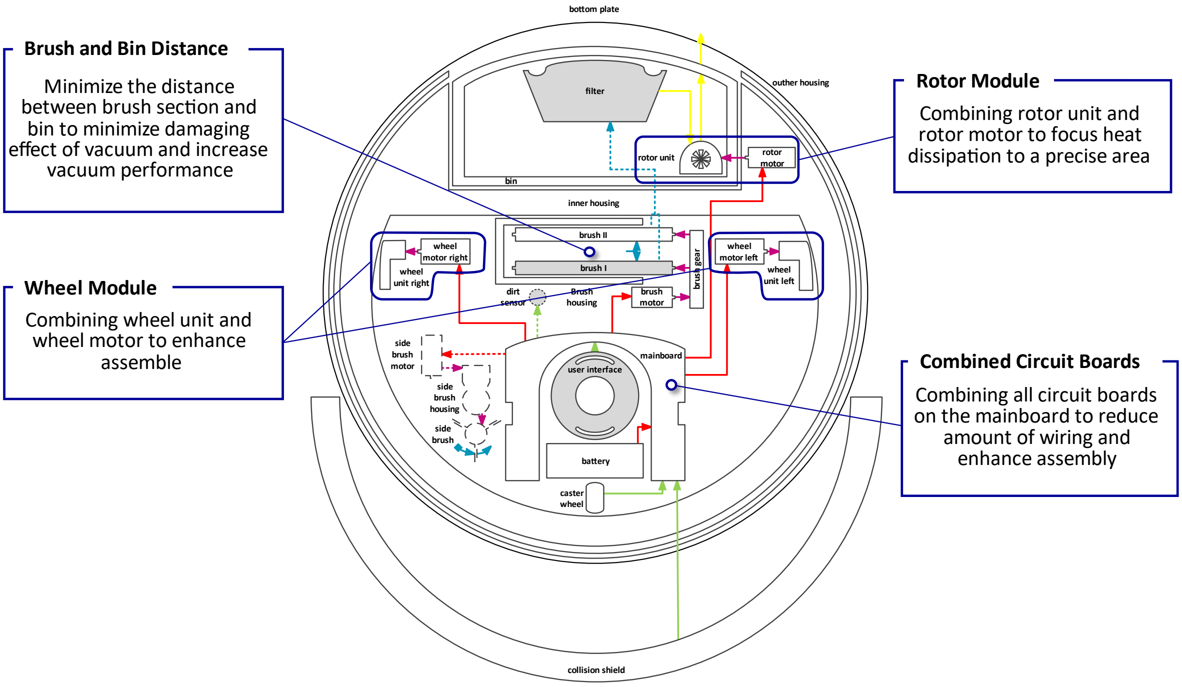
Electrical: For architectural guideline 5 (Electrical), all components that contain/ radiate electrical fields are marked. What is apparent on the MIG is that the electric fields are not contained within modules but are used to cross module boundaries. Motion modules, dirt collection modules and sensor bundles are all interfaced across their module boundaries with electric fields (wires or contactors). All components that are supplied with power must be connected to the battery and each other via cables. Innovations could be considered by bundling these electric fields into modules. Looking at the MIG, one solution could be keeping the electric motors as surface mounted components on the main circuit board module, and then interfacing the motion modules using a gear pair, for example. This would allow the motion module to be a simple gear, shaft and wheel, which would be a much less expensive module and potentially easier to recycle.

Heat: For the architectural guideline 6 (Heat), all components that are on very high or low temperature levels are identified and are marked in. In the case of the robot vacuum cleaner, it is the motors that might emit heat and are marked accordingly. The battery can also potentially heat up considerably. At the same time, batteries are sensitive to low temperatures and if exposed to cold should be insulated.

Gravity: For architectural guideline 7 (Gravity), all components are identified on which gravity exerts a particular influence. In our case, this only affects the dust container, as it can leak and liquids can escape if they are accidentally vacuumed up. In particular, future product variants with a wiping function on the sweeper module, which would then contain cleaning liquids, would be more suitable for the application of this guideline, to keep the wiping below the electronics. Admittedly wiping is currently not yet part of this product example.

Pressure: For architectural guideline 8 (Pressure), all components that must withstand pressure are identified. In our example, these are the dirt tank, filter and rotor which must keep a vacuum and airflow to entrain and move dirt debris. As discussed above with the high force field, the pressure field is currently distributed over two modules. Encapsulating the force field into one module through moving the brushes and air fan into the dust bin module is displayed as solution in the MIG.

In summary, after identifying fields and field-sensitive components, new product concepts can be created. Components and modules can be adapted or rearranged, for example, by changing the component or module itself or their relationship to each other. Here, new concepts can emerge that inhibit the potential for innovation. Considering the architectural guidelines ideas above, we propose a novel concept that takes into account influences from field effects.



Brush and Bin Distance

Minimize the distance between brush section and bin to minimize damaging effect of vacuum and increase vacuum performance

Rotor Module

Combining rotor unit and rotor motor to focus heat dissipation to a precise area

Wheel Module

Combining wheel unit and wheel motor to enhance assemble

Combined Circuit Boards

Combining all circuit boards on the mainboard to reduce amount of wiring and enhance assembly

Figure 5: Adapted MIG with change description.

In the identification of forces (3) and kinematic joints (4), the combination of wheels and wheel motors into one motor is a module proposal with great advantage in ease of assembly due to fewer parts. In the previous product structure, each motor is assigned a printed circuit board. Considering the electrical fields (5), we propose to place all circuit boards on the main board. This has two main advantages. Since the number of cables and wiring within the product is reduced, fewer electromagnetic fields are generated by the cables. The assembly effort can also be reduced, since plugs can be used for the electrical connection, which facilitates assembly. Considering heat (6) and pressure (8), rotor unit and rotor motor are combined into one module. Both components are moving/rotating parts and also heat sources. By combining them into one module, we get fewer interfaces. Looking at the guideline pressure (8), the brush unit should be closer to the tank to minimize the distance of air and dirt flow. The shorter the distance for the transfer of the vacuum from the brushes to the container, the less likely parts get damaged due to the vacuum in the product, and the more efficiently the main function of vacuuming can be performed. The MIG layout for this concept is shown in Figure 5.

4 DISCUSSION AND CONCLUSION

Fields impose constraints on how mechatronic systems can be modularized. The distribution of a field over module interfaces must be carefully engineered considering functional interface requirements and interface geometry to insulate harmful fields while allowing necessary fields which provide desired functions. We conclude that the MIG gives useful visual support to gain new ideas for the rearrangement of the mechanical layouts and module boundaries in comparison to a function structure or DSM. The main strength of the proposed approach lies on its visual component, in contrast with function based (Stone and Wood, 2000) or DSM based structure descriptions. It also allows for the identification of near misses, or areas that are subject to problems in the future if for instance the strength and range of the field changes and additional components are affected by it. Hierarchical tree or matrix-based methods can easily miss those potential interactions.

Furthermore, the example shows that the MIG is a useful tool to visualize fields and to gain a deeper understanding of the influence of field effects on product architecture. The example shows that the MIG is also helpful for representing alternative product structures with modified components and interfaces, a new or rearranged modular structure and to come up new module boundaries to include or exclude components and incorporated functions. The new mapping of functional and structural relationships by moving module boundaries against fields encourages architectural innovation. Studying a product according to the guidelines of which fields are contained in modules and which are distributed across modules provides an opportunity to systematically develop new ideas.

This application of the MIG with superimposed field information is nevertheless limited to early-stage development, when there is still freedom to define modules and design interfaces. It is also limited to 2D representations of the product structure. Additionally, it might be of limited use for practitioners with visual limitations such as colour-blindness. To exploit the full potential of the proposed approach, future research should consider the introduction of the concept of relative field strength and range, as well as relative field sensitivity. The extension of the guidelines to cover other fields such as acoustics, ionizing radiation, etc. and the interactions between different classes of fields also holds promise. Also, real product examples should be developed using the architectural guidelines presented in order to validate to approach.

REFERENCES

Bender, B., Gericke, K. (Eds.), 2021. Pahl/Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung. Springer Berlin Heidelberg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-57303-7

Blackenfelt, M., 2001. Managing Complexity by Product Modularisation. Royal Institute of Technology, KTH, Stockholm, Sweden.

Browning, T.R., 2016. Design Structure Matrix Extensions and Innovations: A Survey and New Opportunities. IEEE Trans. Eng. Manage. 63, 27–52. https://doi.org/10.1109/TEM.2015.2491283

Ehrlenspiel, K., Meerkamm, H., 2013. Integrierte Produktentwicklung Denkabläufe, Methodeneinsatz, Zusammenarbeit, 5th ed. Hanser.

Ericsson, A., Erixon, G., 1999. Controlling design variants: modular product platforms. Society of Manufacturing Engineers, ASME Press.

Gebhardt, N., Bahns, T., Krause, D., 2014. An Example of Visually Supported Design of Modular Product Families. Procedia CIRP 21, 75–80. https://doi.org/10.1016/j.procir.2014.03.162

Hehenberger, P., Vogel-Heuser, B., Bradley, D., Eynard, B., Tomiyama, T., Achiche, S., 2016. Design, modelling, simulation and integration of cyber physical systems: Methods and applications. Computers in Industry 82, 273–289. https://doi.org/10.1016/j.compind.2016.05.006

Krause, D., Gebhardt, N., 2023. Methodical Development of Modular Product Families: Developing High Product Diversity in a Manageable Way. Springer Berlin Heidelberg, Berlin, Heidelberg. 10.1007/978-3-662-65680-8

Küchenhof, J., Schwede, L.-N., Hanna, M., Krause, D., 2019. From Visualizations to Matrices – Methodical support for New Development of Modular Product Families, in: Proceedings of the 21st International DSM Conference. Presented at the The 21st International DSM Conference, The Design Society. https://doi.org/10.35199/dsm2019.11

Küchenhof, J., Seiler, F., Krause, D., 2020. Model Based Early-Stage Assessment for Modular New Product Development, in: DS 103: Proceedings of the 22nd International DSM Conference (DSM 2020), MIT, Cambridge, Massachusetts, October 13th - 15th 2020. Presented at the 22nd International Dependency and Structure Modelling Conference, The Design Society. https://doi.org/10.35199/dsm2020.17

Müller, J.R., Isaksson, O., Landahl, J., Raja, V., Panarotto, M., Levandowski, C., Raudberget, D., 2019. Enhanced function-means modeling supporting design space exploration. AIEDAM 33, 502–516. https://doi.org/10.1017/S0890060419000271

Otto, K., Hölttä-Otto, K., Sanaei, R., Wood, K.L., 2020. Incorporating Field Effects into Functional Product-System Architecting Methods. Journal of Mechanical Design 142. https://doi.org/10.1115/1.4044839

Pimmler, T.U., Eppinger, S.D., 1994. Integration Analysis of Product Decompositions, in: 6th International Conference on Design Theory and Methodology. Presented at the ASME 1994 Design Technical Conferences collocated with the ASME 1994 International Computers in Engineering Conference and

Exhibition and the ASME 1994 8th Annual Database Symposium, American Society of Mechanical Engineers, Minneapolis, Minnesota, USA, pp. 343–351. https://doi.org/10.1115/DETC1994-0034

Sanaei, R., Otto, K.N., Hölttä-Otto, K., Wood, K.L., 2016. Incorporating Constraints in System Modularization by Interactive Clustering of Design Structure Matrices, in: Volume 2B: 42nd Design Automation Conference. Presented at the ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, Charlotte, North Carolina, USA. https://doi.org/10.1115/DETC2016-60510

Sanchez, R., 1996. Strategic product creation: Managing new interactions of technology, markets, and organizations. European Management Journal 14, 121–138. https://doi.org/10.1016/0263-2373(95)00056-9

Schachinger, P., Johannesson, H.L., 2000. Computer modelling of design specifications. Journal of Engineering Design 11, 317–329. https://doi.org/10.1080/0954482001000935

Sinha, K., Han, S.-Y., Suh, E.S., 2019. Design structure matrix-based modularization approach for complex systems with.pdf. Systems Engineering 23, 211–220. https://doi.org/10.1002/sys.21518

Steward, D.V., 1981. The design structure system: A method for managing the design of complex systems. IEEE Trans. Eng. Manage. EM-28, 71–74. https://doi.org/10.1109/TEM.1981.6448589

Stone, R.B., Wood, K.L., 2000. Development of a Functional Basis for Design. ASME, Journal of Mechanical Design 122.

Stone, R.B., Wood, K.L., Crawford, R.H., 2000. A heuristic method for identifying modules for product architectures. Design Studies 21, 5–31. https://doi.org/10.1016/S0142-694X(99)00003-4

Stone, R.B., Wood, K.L., Crawford, R.H., 1999. Product Architecture Development with Quantitative Functional Models, in: Volume 3: 11th International Conference on Design Theory and Methodology. Presented at the ASME 1999 Design Engineering Technical Conferences, American Society of Mechanical Engineers, Las Vegas, Nevada, USA, pp. 247–259. https://doi.org/10.1115/DETC99/DTM-8764

Ulrich, K., 1995. The role of product architecture in the manufacturing firm. Research Policy 24, 419–440. https://doi.org/10.1016/0048-7333(94)00775-3

Verein Deutscher Ingenieure, 1993. VDI-Richtlinie 2221 – Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte.

Williamsson, D., Sellgren, U., 2016. An Approach to Integrated Modularization. Procedia CIRP 50, 613–617. https://doi.org/10.1016/j.procir.2016.04.152

Zamirowski, E., Otto, K.N., 1999. Identifying Product Family Architecture Modularity Using Function and Variety Heuristics. Presented at the 11th Int. Conference on Design Theory and Methodology.