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Flexibility evaluation of modules with a focus on interfaces

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ABSTRACT: In the context of volatile markets, characterised by a need for continuous product development involving module-wise product modifications, the importance of flexibility as an attribute of products and their production system has been increasing. This paper presents a methodological approach focusing on the flexibility evaluation of modules regarding their interfaces. The subject encourages engineers and researchers to analyse and rethink the interface design and the location of module boundaries regarding change propagation. The method was validated using the Design Method Validation System (DMVS) to determine its usefulness, applicability and acceptability. The design workshop for validation was applied to a product family of trunk lids by employees of a German car manufacturer.

KEYWORDS: Flexibility, Decision making, Design process, Design engineering, Design for interfaces

1. Introduction

Technological evolution and changing customer needs are the drivers for continuous product development. The integration of product modifications is a complex task that requires the collaboration of engineers from different departments. In addition, the transition from mechanical products to mechatronic systems has increased the complexity of both products and development processes due to the necessity of multi-disciplinary collaboration. Numerous interdependencies must be considered by the multi-disciplinary and cross-departmental team (Zuefle et al., 2023).

The product's interfaces, especially those between modules, are strategically important to avoid the propagation of change from the module under redesign to the rest of the product (Sanchez, 2004). Given the intrinsic nature of interfaces generated during design for the later joining processes in the production and physically created in the production system, it is essential to consider the potential change propagation in the product and into the production system via the interface.

This contribution presents a validation experiment for a new modularization approach that supports engineers in designing modular product families with greater flexibility. The method builds upon Krause et al.'s Design for Variety and Life Phases Modularization (Krause & Gebhardt, 2023) and incorporates additional method steps to guide engineers towards the creation of flexible product structures. These steps include the identification of flexibility drivers and the flexibility evaluation of modules with a focus on interfaces which invites the engineers to analyze and rethink the interface design and the location of module boundaries to facilitate the module-wise modifications of complex products. The focus lies on evaluating modules regarding their interfaces with other modules, whereas interfaces between components within a module are not considered. The research question of this contribution is to prove the validity of the method.

In the following section, the research background is laid out. Afterwards, the methodological approach is briefly explained, and the results of a design workshop to test the method are presented and discussed. The paper concludes with a conclusion and outlook.

2. Research background

The facilitation of product variant design, including subsequent generations, is a widely discussed topic in literature, with many approaches proposed. The following presents and discusses a selection of development approaches, considering their respective usefulness in increasing flexibility.

2.1. Modular product design

Modular product structuring has proven useful in many ways to counter complexity. Dividing a product into smaller parts can enable parallel working, which can shorten development times and help ensure that products can be changed more easily in subsequent product generations, increasing the organization's flexibility (Sanchez & Mahoney, 1996; Suárez et al., 1991).

2.1.1. Product structuring

To quantify the costs of product variety and to support developing products that incur minimum variety costs, Martin and Ishii developed a Design for Variety (DFV) methodology (Martin & Ishii, 1996; Martin et al., 1998). Krause et al. take up on this, use variety allocation from customer requirements to product components and bundle the variety-induced complexity in modules (Krause & Gebhardt, 2023). In this approach, technical-functional aspects and product-strategic aspects are taken into account.

2.1.2. Assembly and production processes

Variety in product design and the manufacturing of a product are closely linked. Various functional and strategic drivers can be considered when designing product architecture concepts such as platforms. Jiao et al. (2007) emphasize the importance of a viable production design to enable mass customization in manufacturing through process platforms. They propose to create a generic product structure and a generic process structure that are harmonized. Variant parameters are identified in order to find product variants with suitable production processes. The dilemma remains with the unknown future variance, which causes frequent design changes. Halfmann et al. (2012) support the development of modular product architectures by incorporating production strategies for variety. They use concepts of commonality and postponement to effectively manage product variety in production. These strategies can also be used to develop new modular products with a high future variety of variants. Core and variant processes are identified to overcome uncertainties and allow future flexibility for variant design. They can be iteratively harmonized with a generic product family concept (Küchenhof et al., 2020).

2.1.3. Matrix-based structuring and change propagation

Matrix-based structuring is an effective way to deal with the complexity of systems. Common approaches include using the Design Structure Matrix (DSM) in many contexts (Browning, 2016). Pimmler and Eppinger (1995) demonstrated a comprehensive approach to product design through their integration analysis method. Matrix-based structuring based on the DSM can be used for product structuring and linking different design domains. Structural complexity management is a suitable method for managing dependencies between system elements in a domain and for elements between system elements from different domains. Suh (1998) models and connects the customer, functional, physical, and process domains in his axiomatic design. The connection from the physical to the process domain can describe the transition from a product to a production process. Mertens et al. (2021) combine requirements with production technology in their extended axiomatic design to evaluate different product concepts. Other methodological approaches that consider the product and the process are the House of Quality and Function Deployment, in which customer needs are mapped with design attributes, costs and feasibility (Hauser, 1993) and the Demand Compliant Design (DeCoDe). The main matrices used in DeCoDe combine functions, components, and processes (Sitte & Winzer, 2011).

In complex systems, a change at one point can have far-reaching consequences in other areas of the system. To comprehensively analyze change and its progression through complex systems, methods of change propagation have been developed to help analyze the cause and effect of change processes in technical systems (Eckert et al., 2004). When designing systems for changeability, DSM can be used to model the reference system and track changes. De Weck (2007) introduces the Change DSM to anticipate changes and the Delta DSM to capture changes retrospectively. Orawski et al. (2012) adapt the SCM to achieve consistency between requirements engineering and life cycle management. Requirement modules and life cycle planning were linked by matrix subtraction to identify change propagation through the domains, increase the efficiency of product planning and improve early design phases (Orawski et al., 2012).

Even if the effects of changes are analyzed in the approaches presented, this is usually based on estimating the degree of coupling between components or modules. No further categorization is provided to classify either the functional interaction or the geometrical design of the interfaces in terms of redesign. As a result, there is no guidance on how the interface contributes to change propagation and redesign efforts.

3. Methodological approach

A comprehensive approach for evaluating flexibility, considering the interface design in highly complex products such as automotive systems, is presently nonexistent. As outlined by Beibl and Krause (2024b), a product's degree of flexibility remains challenging to assess. Their findings indicate that the evaluation scheme is either based on estimations or the product's robustness respective to anticipated future changes rather than on more objective and generally applicable criteria.

Therefore, a methodological approach was developed to support engineers in designing modular product families with greater flexibility. In particular, the method is intended to leverage the flexibility potential offered by digitalization, automation, and novel structures of production systems through appropriate product family design. It is assumed that the new and flexible modular product family must not be developed from scratch but that the engineers can build on data from existing products from the company or the market. The method is based on Krause et al.'s Design for Variety and Life Phases Modularization (Krause & Gebhardt, 2023), focusing on the life phases 'product development' and 'production'. In line with the contribution's focus on the flexibility evaluation of modules regarding the interfaces, the description of the methodological approach is confined to the three method steps for the life phase 'product development': the analysis of current concepts, the concept development, and the flexibility evaluation of the developed concepts.

A description of the method steps designed for the life phase 'production' can be found in preliminary studies by Beibl and Krause (see Beibl & Krause, 2024a and Beibl & Krause, 2024b).

In **method step 1**, the development engineers get an overview of the external product variety and how it is realized by components to reenact the propagation of change coming from product properties. Therefore, the Feature Allocation Model (FAM) is used, which depicts the relation between the product features and components as well as the components' variant characteristics (Küchenhof et al., 2022). Renderings of the contemplated product family are used to identify change-critical aspects such as the load paths, components in common use and appearance components. **Method step 2** is based on the Life Phases Modularization, where components are clustered according to technical, functional, and strategical aspects from the perspective of the different life phases (Krause & Gebhardt, 2023). From these clusters, modules are derived. The results from the analysis of the current concepts in method step 1 build the basis for the clustering categories and thus guide the definition of modules. The developed concepts are then evaluated regarding flexibility in **method step 3**. Table 1 shows the evaluation of the concepts regarding the neighborly relationship N_{Mi} of their modules and their interface design I_{Mi}. The overall flexibility key figure F can be derived from Table 1, according to Equation 1. To ensure the comparability of concepts with diverging amounts of modules, the key figure is normalized via the division through the concept's amount of modules n.

$$F = \frac{\sum_{i=1}^{i=n} F_{M_i}}{n} = \frac{\sum_{i=1}^{i=n} (N_{M_i} + I_{M_i})}{n} \quad (1)$$

Throughout the entire method step 3, the two criteria are to be evaluated in accordance with the following rating scale: "not flexible" (1 Point), "moderately flexible" (3 Points), or "flexible" (9 Points). Thus, the flexibility score F can range from 2 (low flexibility) to 18 (high flexibility).

Table 1. Template for the flexibility evaluation of a product concept

Module name	N_{Mi}	I_{Mi}	F_{Mi}
M1: Module 1			
M2: Module 2			
. . .			
F			

In terms of the neighborly relationship, a module is defined as flexible if all the components of the module are located within one area of the product. Concentrating a module's components in a single area minimizes the number of interface partners and reduces the risk of change propagation. Conversely, if the components of the module are distributed across the entire product in a partial or widespread manner, the module is defined as moderately flexible or not flexible. Accordingly, the greater the product's flexibility, the higher the key figure neighborly relationship N_{Mi}.

The **interface design** of a module I_{Mi} is defined by the sum of all its interfaces shared with other modules within the product, divided by the amount of module partners P_i (see Equation 2). A symmetric matrix evaluates the relations between all the product's modules (non-directional). Table 2 provides an overview of the flexibility evaluation of each module interface of the product. The interface design I_{Mij} of the interface between module M_i and module M_j is characterized by the contact surface C_{Mij} and the joining technology T_{Mij} (according to Equation 3). If a module shares more than one interface with another module, the interface design with the lowest score is considered in the evaluation matrix.

$$I_{M_i} = \frac{\sum I_{M_{ij}}}{P_i} \tag{2}$$

$$I_{M_{ij}} = \frac{C_{M_{ij}} + T_{M_{ij}}}{2} \tag{3}$$

Table 2. Template for flexibility evaluation in terms of interface design

$I_{M_{ij}}$	M1	M2	…
M1	☒		
M2		☒	
…			☒

Contact surfaces designed as form-fit and circumferential contact surfaces are defined as "not flexible" as they require a high degree of coordination in design to match the two interface partners. Meanwhile, point contact surfaces are defined to be "flexible" with regard to product modifications since the module to be modified can be easily fitted to the geometry of its mating partner. Interfaces, realized via adapters in the shape of standardized mating connectors or auxiliary components, provide moderate flexibility regarding product modifications. Standardized mating connectors ensure combinability and auxiliary components such as mounting brackets are easily redesigned (Uckun et al., 2014). The joining technology also encompasses varying degrees of freedom concerning product modifications. Welded, soldered or adhesive bonds, for example, can somewhat compensate for a misfit of the modified module. The highest flexibility is achieved by Metal Deposition, which is used as a joining technology. The use of additively manufactured interfaces can compensate for the geometrical misfits of the mating modules, which allows for a higher degree of freedom in design. Joining technologies such as screw, clip, or plug connections solely require a thread or hole on the mating partner, which are usually easy to adjust or add and thus defined to be "moderately flexible". In contrast, spot-welded, rivet, or clinch bonds, which are usually used in combination with adhesive bonds in the automotive industry, require much effort to coordinate the flange of the mating modules. These interfaces provide a high risk of change propagation to the mating partner and are thus defined as "not flexible".

4. Conduction of the design workshop

The presented method was applied in a design workshop for the purpose of validation, which was conducted at a German car manufacturer. Five participants with professional experience in design and product development but little knowledge about modularization methods applied the presented method to a product family of trunk lids. The task was to develop new concepts for the trunk lid that would be easier to modify in the future, regardless of the nature of the change request. The new product family will be produced in a modular, lineless production system offering higher flexibility than the current conventional system. It is therefore important to consider both the product development and production process perspectives during the conceptualization phase.
The validation procedure was designed according to the Design Method Validation System (DMVS) by Üreten et al. (2020). The objective was to ascertain the presented method's usefulness, applicability and acceptance in industrial applications. Regarding the dimension of usefulness, the hypothesis is to be proven that the presented method supports the engineer in developing products that comprise greater flexibility regarding change integration. An observer documented how the team approached and completed the task to evaluate the applicability of the design method procedures and materials. To prevent the study from being compromised by the influence of the method developer, the team comprised one method expert, who was provided with a briefing before the workshop. The method in question was explained via an illustrative example consisting of data from the front door. The method expert's role was to guide the team through the method steps. The method acceptance was determined by a questionnaire that ascertained the willingness to apply the method in similar cases and to recommend it to others.
The design workshop started with a short welcoming speech and an introductory round of the participants. This was followed by a brief introduction to the topic and an explanation of the method based on the illustrative example of the front door presented by the method developer. The objective was to ensure that all participants possessed a common understanding of the topic and a similar level of knowledge. At first glance, the door and the trunk lid appear to share certain similarities. However, it is impossible to convert the door's modular structure to serve as a solution for the trunk lid. After that, the participants commenced the assigned task, under observation. Upon completing the task, the participants completed a questionnaire regarding the methodology's usefulness, applicability, and acceptance. The design workshop concluded with presenting the team's results and an oral feedback round.

4.1. Baseline design

Data from an existing product family of trunk lids was provided as a baseline model. The components of the trunk lid are distributed over twelve modules, as shown in Table 3 and Table 4. The concept reaches a flexibility score F of 8. The individual flexibility score F_{Mi} of the modules ranges from 4 to 12. Some modules, such as the rear window, the wiper unit or the user interface module, reached the maximum value concerning the neighborly relationship. With regard to the interface design, the modules reach values of 2 to 6. Most module interfaces are categorized as not flexible due to circumferential contact surfaces. The modules are assembled via screw and clip connections which results in lower values for the interface design I_{Mi}.

Table 3. Flexibility evaluation of the baseline concept

Module name	N_{M_i}	I_{M_i}	F_{M_i}
M1: Trunk lid body construction	1	3	4
M2: Auxiliary lights	3	3	6
M3: Rear lights	1	6	7
M4: Rear window	9	3	12
M5: Wiper unit	9	2	11
M6: Wiper drive unit	9	3	12
M7: Rear window seal	9	2	11
M8: Hinge / Gas spring	1	4	5
M9: Rear spoiler	1	3	4
M10: User interface	9	3	12
M11: Cover	3	2	5
M12: Wiring harness	1	6	7
F			8

Table 4. Flexibility evaluation of the baseline concept in terms of interface design

$I_{M_{ij}}$	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
M1		2	6	2	x	3	2	2	2	2	2	6
M2	2		x	2	x	x	x	x	2	x	x	6
M3	6	x		x	x	x	x	x	x	x	x	6
M4	2	2	x		2	x	2	x	2	x	x	6
M5	x	x	x	2		2	x	x	x	x	2	x
M6	3	x	x	x	2		x	x	x	x	2	6
M7	2	x	x	2	x	x		x	2	x	2	x
M8	2	x	x	x	x	x	x		x	x	x	6
M9	2	2	x	2	x	x	2	x		x	x	6
M10	2	x	x	x	x	x	x	x	x		2	6
M11	2	x	x	x	2	2	2	x	x	2		x
M12	6	6	6	6	x	6	x	6	6	6	x	

4.2. Concept development for flexibility

In the design workshop, the participants analyzed the provided information about the product family of trunk lids according to method step 1. The FAM of the trunk lid shows that its components are highly connected and cannot be changed independently. The provided renderings of the product family were used to compare the trunk lid variants for a better understanding of the differences. The team highlighted the load paths, relevant for the design of the trunk lid body construction, and communal components, which can be used across the product family. Regarding enabling a quick reaction to market changes and module-wise modifications of the trunk lid, the team decided to distinguish between appearance-related components and those contributing to the trunk lid's functionality. Therefore, the team defined three sections in the trunk lid to separate the inner and outer components from the trunk lid's core.
Based on that, the team defined corresponding module driver specifications and clustered the components accordingly. About technical functional coupling, the team generated one cluster for the body structure/ crash, which contained all metal components; one for mechanics such as the hinge, the gas spring, the wiper mechanics, etc.; one for signal and energy supply, which consists of the wiring harness and one for the user interface which covers the handle strip.
The exterior and interior components were clustered separately under the module driver Styling according to Erixon (1998). Furthermore, the team built a cluster of components influenced by the type of trunk lid (depending on the limousine or hatch car model). This cluster covers almost all components except the wiring harness and the cluster of communal components, such as the handle strip, the third brake light, and the license plate light.
Based on the component clusters, the team defined the following six modules: Module 1 Trunk lid mechanics, Module 2 Trunk lid body structure, Module 3 Trunk lid exterior skin, Module 4 Trunk lid interior skin, Module 5 Electric/ electronics, Module 6 Water management.

4.3. Evaluation and selection of the best concept

The team was uncertain about the appropriate module size with regard to flexibility and discussed whether to refine the modules and develop a second concept. Due to the limited remaining time of the workshop, they decided to continue with their concept.
The results of method step 3 are presented in Table 5 and Table 6. With regard to the neighborly relation, the team evaluated each module with 3 points for moderate flexibility, since the components of each module are distributed over a large area of the trunk lid but not in all three dimensions.
The values of the interface design of the modules vary between 4 and 6. The team explained that they defined interfaces of low complexity. However, the contact surface is circumferential in most cases, which results in a low value for the key figure C_{Mij} and thus I_{Mi}. The reallocation of the rear light and its carrying structure to the trunk lid exterior skin was highlighted as a key aspect enabling flexibility. This concept allows changes to the rear lights without affecting the trunk lid body structure. Moreover, the trunk lid exterior and the interior skin can be changed independently of the trunk lid body structure, provided the interfaces are maintained. The interfaces of functional components are designed as clip or screw connections.

Table 5. Overview of the flexibility evaluation of newly developed concept

Module name	N_{M_i}	I_{M_i}	F_{M_i}
M1: Trunk lid mechanics	3	6	9
M2: Trunk lid body structure	3	6	9
M3: Trunk lid exterior skin	3	4	7
M4: Trunk lid interior skin	3	6	9
M5: Electric / Electronics	3	6	9
M6: Water management	3	5	8
F			9

Although the newly developed concept comprises half the number of modules as the current concept, it achieves a slightly higher value for the overall flexibility F with a score of 9. The application of the evaluation made the team question the defined interfaces and module boundaries. Some team members said they would like to apply the method again and refine the modules. They realized smaller modules are more manageable to decouple and ease the development and integration of module-wise product changes.

Table 6. Flexibility evaluation of the newly developed concept in terms of interface design

$I_{M_{ij}}$	M1	M2	M3	M4	M5	M6
M1		6	x	6	6	x
M2	6		5	6	6	6
M3	x	5		x	6	2
M4	6	6	x		6	x
M5	6	6	6	6		6
M6	x	6	2	x	6	

5. Evaluation and discussion of the workshop results

The workshop results are discussed in the following focusing on the validation dimensions of usefulness, applicability, and acceptance of the method. The evaluation is based on the recorded results, the observer's documentation, the questionnaire, and the participants' comments during the oral feedback round.

Usefulness

The questionnaire results reveal that the method, with its structure and visualization tools, supports the engineer in developing a flexible product family under consideration of the production system (4 out of 5 participants). Moreover, the participants (5 out of 5) perceived the method to have a stimulatory effect on their creativity during concept development. The participants (3 out of 5) acknowledge the method's guidance in identifying change-relevant aspects and flexibility potentials. The usefulness of the clustering process was confirmed unanimously (5 out of 5 participants). Furthermore, the participants confirm that the evaluation scheme allows a simple (3 out of 5) but profound (4 out of 5) evaluation of the developed concepts and comparison with alternatives. The recorded results show significant differences between the developed concept and the baseline design of the trunk lid. However, one participant stated that a repeated application of the method on the same scope – like an iteration – would improve the result. As mentioned before, the participants realized how to improve their concept in terms of flexibility after completing method step 3. Besides, the participant suggested to practice the method before its application in an actual use case to achieve better results. The observer's notes reveal that the participants discussed further concept alternatives without recording them. They discarded these ideas immediately for cost reasons, although the task was to leave costs aside. The observer confirmed that method step 1 led the team to identify flexibility potentials and thus module driver specifications for method step 2. The participants were able to transfer their findings from method step 1 to subsequent steps and complete the task guided by the provided materials.

Applicability

The applicability of the method is evidenced by the comments of the observer and the questionnaire findings, which are in alignment. The observer documented that the participants were able to solve the task with the provided materials and followed the description of the method steps. All the participants (5 out of 5) confirmed the comprehensiveness and applicability of the method, including the provided materials, introduction, and explanatory examples. However, the application of this method appears to be accompanied by a certain degree of insecurity, as evidenced by the questionnaire results, which revealed

that only 2 out of 5 participants confirmed that the method was carried out confidently. During the feedback round, the participants emphasized the complexity of the method itself and the application example. Some training in advance or guidance by a moderator would be helpful when applying the complex method for the first time. Similarly, easier access to the basic data distributed throughout the company could lead to a more straightforward introduction to the underlying data used in the method regarding flexibility. Using model-based approaches for product families could provide a basis for data collection and maintenance (Berschik et al., 2024). At a certain point, the team's focus on flexibility was diverted by discussions about the costs of proposed concept alternatives. In such a situation, a defined moderator within the team can guide the discussion back to the assigned task to focus on flexibility and neglect costs.
Furthermore, the observer noted some potential for improvement concerning the wording in the provided materials. Another suggestion was to integrate the flexibility evaluation in the analysis of the current design in method step 1. This would sharpen the focus on flexibility aspects while developing new concepts in method step 2. Overall, the processing time of three hours was sufficient for the team to complete the task, as the observer's documentation reveals.

Acceptance

The findings of the questionnaire demonstrate a high degree of acceptance in terms of willingness to utilize the method in future studies. All participants indicated that they would apply the method for a similar task and recommend it to others, except one (4 out of 5). Furthermore, all the participants (5 out of 5) confirmed that a comprehensive analysis of the developed concept would be reasonable and beneficial for the company. As mentioned before, during the feedback round, a proposal was put forth to repeat the workshop and refine the developed concept. As evidenced by the observer's field notes, the participants displayed a high level of motivation in their pursuit of the assigned task.
The conducted design workshop for validation proves the method's usefulness, applicability, and acceptance in an industrial use case.

6. Conclusion and outlook

The necessity for continuous product development and modification on a modular basis in the context of volatile markets underscores the significance of flexibility as an attribute of the product itself. The objective of existing methodological approaches is to facilitate the derivation of new product variants or planned subsequent generations. In contrast, the presented method considers the module interfaces to facilitate the integration of unknown future changes from the perspective of product development and novel production systems characterized by a high degree of digitalization, automation, and flexible structures. Based on a guided analysis of the current design, modules are designed for flexibility, building upon the so-called Life Phases Modularization. In the subsequent step, these modules are evaluated with regard to flexibility. Therefore, matrices are used to evaluate the product's modules in terms of neighborly relations and interface design, whose flexibility in the redesign is characterized by the contact surface and the joining technology. The method was subjected to a validation process in a design workshop, following the guidelines of the DMVS. The method's application in the industrial use case of the trunk lid product family has proven its usefulness, applicability, and acceptance. This contribution solely presents the validation of the steps of the method that are relevant for the life phase of 'product development'. However, the method contains steps for the life phase 'production', which considers the challenges of production engineers and the design of new assembly concepts for flexibility.
The authors recommend conducting further applications of the method on different products to ascertain its universal usability. Concerning the complexity of the multi-disciplinary development processes, a refinement of the evaluation scheme in terms of further distinction of the interface types, namely spatial, energy, information and material interaction, would be a valuable addition to the existing framework. Additional research is required to document and visualize the interfaces for subsequent development steps while converting the concept into a specific design.

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