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Appropriate consideration of interfaces in product development

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Abstract

The development of modular product families depends on correctly implementing appropriate interfaces. They exert a significant impact on the configurability of products, the interchangeability of modules, and the production processes and respective equipment. This paper analyses interfaces of modular product architectures from a strategic perspective and discusses the impact of these interfaces on sustainability and module-wise product modification of modular product families. In this context, it presents an enhancement of the module interface graph (MIG) for more effective treatment of interfaces in product development, based on two case studies in different fields of application.

Keywords: Interfaces; Product Development; Sustainability; Production

1. Motivation

The way products are developed has changed a lot recently. Products are no longer seen as separate entities. It is no longer the case that products are regarded as standalone entities. Instead, they are regarded as complex, interconnected systems that are expected to function seamlessly across a range of domains and disciplines. A notable trend has emerged, whereby the complexity of products is consistently increasing. This is primarily driven by the demand for smart, interconnected systems and the necessity for interdisciplinary integration [1]. This evolution is clearly evident in the growing number of interfaces that must be considered and managed throughout the product development process.

The functionality of interfaces plays a crucial role in determining the adaptability, scalability, and overall success of product families. This is particularly evident in a market environment that is characterized by rapid technological advancements and shifting consumer demands [1].

Despite the widespread recognition of the importance of interfaces in the literature, there remains a notable gap in the focus of interfaces during the product development process [2]. This lack of attention can result in increased costs and a reduction in product quality. A notable challenge arises from the necessity of integrating interface considerations within the tools and methodologies that are commonly employed in product development. The limitations of conventional tools in adequately addressing the demands of interfaces in product development result in inefficiencies in the coordination between interacting components and disciplines.

To address this gap, it is essential to enhance the capabilities of product development tools in order to ensure that they are adequately suited to support the consideration of interface within the product development. This requires the integration of advanced techniques for defining, analyzing, and optimizing interfaces, enabling product developers to anticipate and mitigate potential integration issues at an early stage of the development process. By emphasizing the importance of interfaces within product development tools, it is possible to significantly enhance the synergy between components and modules and thereby accelerate the development process and produce more robust and competitive products.

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2. Research Background

In the field of product development, interfaces represent a crucial point of convergence where disparate components, typically developed independently, must operate in an integrated manner. The quality of these interfaces can have a significant impact on a product's overall performance [3]. Furthermore, interfaces are of great importance in the management of a product's lifecycle, exerting influence not only on the initial design and integration phases [4], but also on manufacturability [3], subsequent maintenance and upgrade processes [5], as well as recycling. The design of interfaces with compatibility in mind can result in enhanced modularity, whereby modules can be developed, tested and upgraded independently, thus fostering innovation and flexibility [6]. Interface standardization and decoupling are two of four characteristics of modularity and can be directly influenced by the interface design [7].

In the context of product design, interfaces are considered at different architectural levels, such as functional, component and module level. At the functional level, an interface can be defined as the boundary between two or more functional elements that interact with one another [8–10]. Ullman posits that product functions are primarily realized at their interfaces, yet the complexity of products often arises most frequently at these interfaces [8]. At component or module level, an interface represents the physical manifestation of a functional interface, depicturing the area of interaction between components or modules [2].

Moreover, there is a nuanced differentiation between interfaces and interactions in literature. An interface is characterized as the boundary of a module or component. In contrast to that an interaction refers to the input and output relationships between these components, indicating a flow or exchange of material between them [11]. Further distinction can be made concerning the purpose of the interface. Products contain interfaces that are shared between their components to realize the product‘s functions, but also those relevant for production processes. These production interfaces are necessary for component handling or fixation during the life phase production. With regard to compatibility, the variety of components, especially of their interfaces, is a crucial design characteristic and of strategic importance [11].

Gebhardt emphasizes the importance of appropriate visual support for product development tasks and presents a method to design visualization tools matching with the development task, users and stakeholders as well as design goal [12]. The purpose of the visualization is to support the engineer in his task and the facilitating cross-disciplinary conversations by depicting a simplified model of the product focused on task relevant information and highlighted aspects [12].

Various visualizations have been developed for product design tasks which depict interfaces in various ways. A literature review conducted by Parslov and Mortensen [2] summarize the different perspectives and definitions of interfaces. Interfaces which are seen as interaction of components or modules are usually depicted as flows in the shape of arrows with further textual description or color coding of their function, as illustrated in [13,14]. Others use the same classification but depicted as an entry in a component module matrix to capture the interface [15,16].

Parslov and Mortensen discuss the relevance of the functional meaning of interface versus their strategical meaning in the context of product life phases, especially in the context of product changes [2]. The design of interfaces across different engineering disciplines is also of strategic importance [2]. Interface can be used as an indicator how changes propagate in a product [17] and impact production processes [18]. With regard to strategic aspects, other characteristics of interfaces such as variance, joining information for production and recycling gain importance and need to be visualized.

Some authors already distinguish between optional and non-optional interfaces by highlighting optional interfaces using dashed lines for the arrows [14,19,20]. Furthermore, Harlou integrated information about the varying specifications of interfaces, such as voltage and frequency for wiring, in the BOM-like visualization called Product Family Master Plan which contribute to the realization of customer-relevant variant product properties [21]. Mikkola extends the view by a distinction between fundamental and optional linkages, whereby optional linkages are expressed by dotted lines [22].

There are several presentations of geometrical descriptions of interfaces with focus on the contact area or active area in the shape of illustrations, 2D drawings or renderings from CAD models [2,17,23–25]. The detailed description and classification of contact areas is of relevance for the design for assembly and the function surface of components with relative motion. In the context of mechatronic products, Beibl et al. discuss that interfaces such as wiring require more attention in the development process and thus were considered as an entity equal to components [20]. Parslov and Mortensen provide further theoretical discussions [2].

3. Research Question

However, existing approaches such as DfX primarily address the functional and variant characteristics of products or components in general, but do not sufficiently take into account the strategic importance of interfaces. The presented functional and geometrical description of interfaces do not provide sufficient information for with regard to the higher frequency of product modifications and increasing importance of sustainability. Further distinction of interfaces is required in terms of variety, combinability and their influence on assembly and disassembly regarding production, product maintenance and recycling, which leads to the research questions:

1. What aspects of interfaces impact strategic product development and how, in terms of sustainability and module-wise product modification?
2. How can the visualization of interfaces can be improved to support the appropriate consideration of strategical aspects during the product development process?

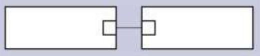
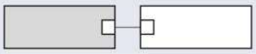
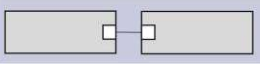
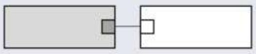
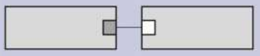
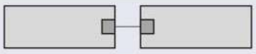
Possible combinations	Explanation
	In a vacuum robot the motor controller (SC) has an electrical interface to the motors (SC). The electrical interface consists of a plug (SI) and a socket (SI)
	Mobile phones (VC) have an electrical interface to the charger (SC) with an USB-C Socket (SI) and USB-C Plug (SI)
	Drilling machines (VC) have an mechanical interface to the drill (VC). The interface consists of the drill chuck (SI) and the drill (SI) itself.
	The tailgate lock of car has a mechanical interface consisting of a bracket (SI) and a latching mechanism (VI)
	A shelf consists of shelves (VC) and shelf walls (VC). The shelf walls have a mechanical interface to the shelves in the form of holes (SI). The interface of the shelves consists of shelf holders (VI) that are screwed or plugged in.
	A cooling circuit consisting of a water pump (VC) and a heat sink (VC) have a material interface to exchange water. The interface consists of fittings (VI) and hoses (VI).
SC: Standard component VC: Variant component	SI: Standard Interface VI: Variant Interface

Figure 1: Combinations of components and interfaces regarding variety

4. Analysis of Interface Visualization

In order to address these questions, it is necessary to distinguish between standard and variant interfaces. The authors posit that the Module Interface Graph (MIG) is an especially suitable visualization tool for the development of modular product architectures and can be extended effectively with regard to the consideration of different interface types.

In model-based approaches, ports can already be used to map the (electrical) inputs of a system block. These ports are represented by squares at the boundary of a system block, via which interactions with other blocks are possible. Variety is not taken into account in this representation.

The distinction between variety and standard is typically differentiated in the MIG by the coloring of the components. A white background indicates a standard component and a grey background indicates a variant component. These two visualizations can be merged in the MIG by using ports to visualize the interfaces and characterizing the variety of this interface via the background color.

Figure 1 illustrates this visualization and provides an overview of the full range of potential component-interface combinations in terms of variety. A combination of a variant interface with a standard component is not compliant with the definition of a standard component. In this view, standard shares in variant components are also taken into account, which allows a more detailed information and provides support for a well-balanced modularization process.

Interfaces are always part of a component and are displayed accordingly as part of this component. Interfaces are typically not optional, but are always present in a component. Interactions between interfaces, on the other hand, are often optional, as components eliminate oversized interfaces that are only used in individual product variants. The illustration of optional interactions can be adopted from literature using dashed lines. As already discussed in section 2, the distinction between product and production interfaces is important for strategic reasons, as special focus must be placed on interfaces that are production interfaces in product development. Another important characteristic of interfaces is the distinction as to whether they are implemented through detachable or non-detachable connections. This has an enormous influence on the production processes in production, but also on disassembly for reuse or recycling. In order to take these distinctions into account in product development tools, the authors propose a visualization, which is presented in Figure 3.

This visualization approach is applied to two case studies, the crown module of an aircraft and the trunk lid of a car. The first study focusses on the crown module (CM), which is the attachment structure of the over-head storage compartment (OHSC) in an aircraft cabin. The position and connection of the CM is visualized in Figure 2.

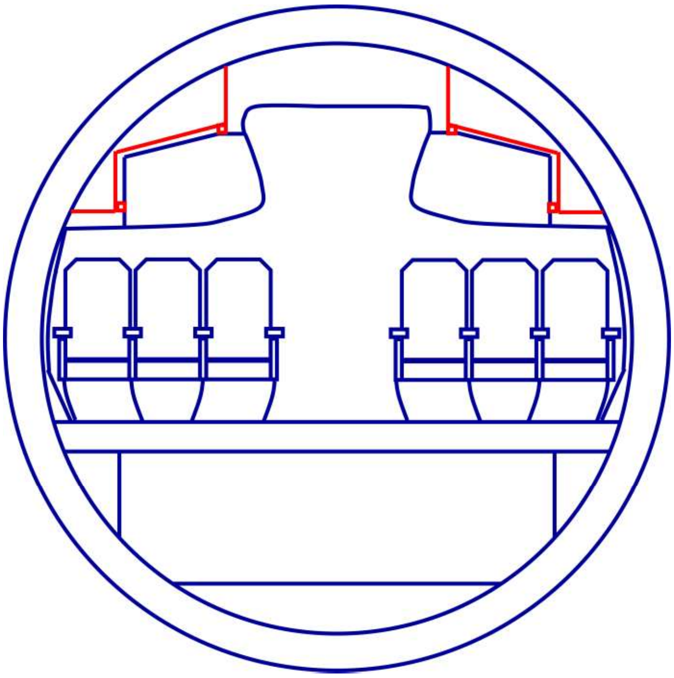


Figure 2: Cabin of an aircraft with highlighted position of the crown module

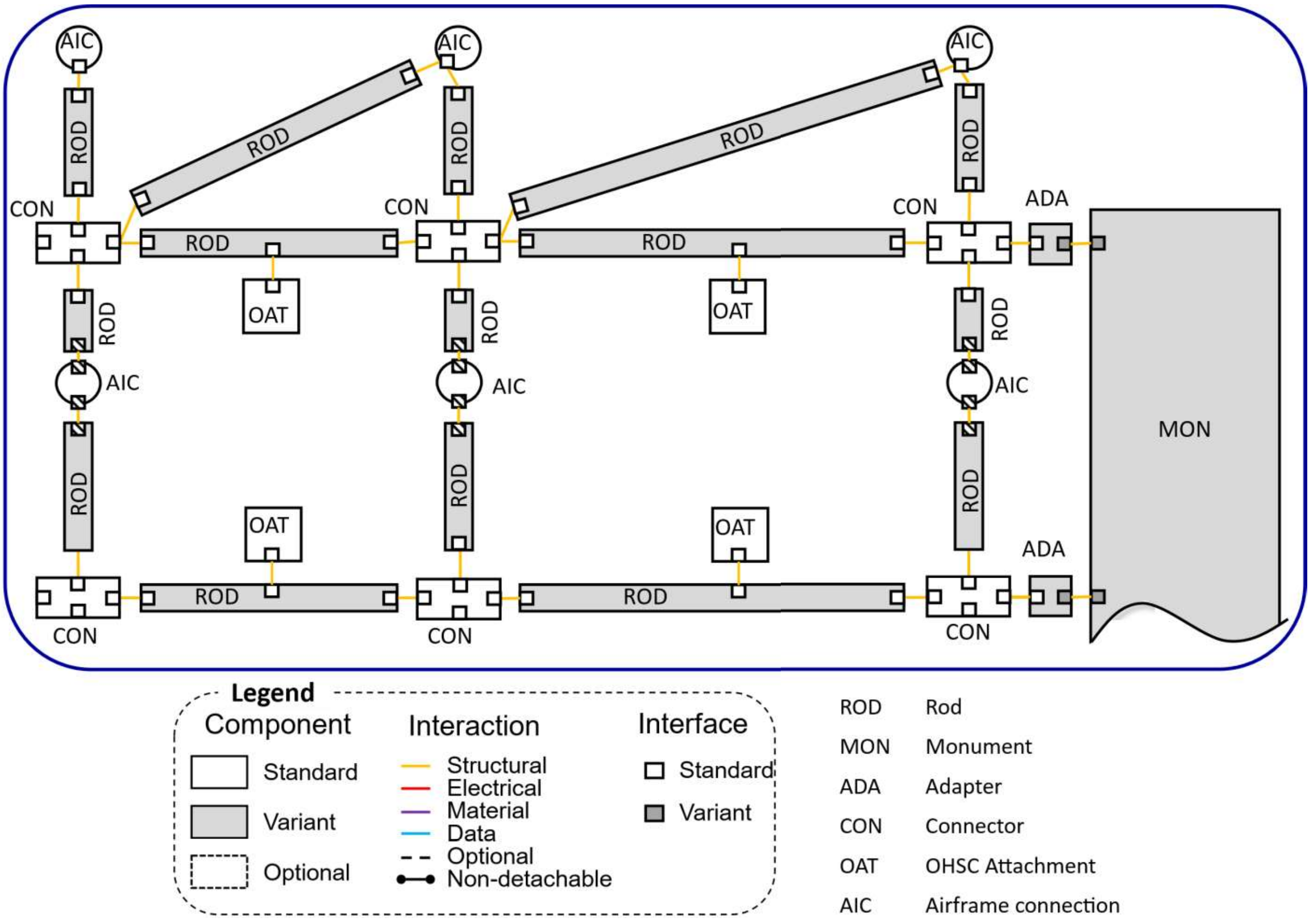


Figure 3: MIG of the crown module

To ensure a standardized structure for attaching the overhead storage to the primary aircraft structure, standardized interfaces are important, but at the same time a flexible connection of variant cabin structures is needed. It is therefore essential to consider the interfaces specifically during development. The CM is made up of rod units that are repeated along the aircraft. The length of the rods can vary based on different OHSC sizes. Other cabin monuments, such as a lavatory, can also be connected to the CM. For simplicity purposes only the mechanical connections are considered here. As can be seen in Figure 3, the different rod lengths result in a variety of these rods. However, the consideration of interfaces in the MIG shows that many of the interfaces are standardized and all of them are detachable since screws are used for the connection. This consideration allows a distinction to be made between component and interface variety. A variant component with a standardized interface enables independent development of the components and retention of the assembly processes despite the component variance. In the example shown in Figure 3, the connection of a monument can be seen on the right. The monuments are usually variant and the interfaces cannot be standardized either since the dimensions and the connection principle changes. In order to nevertheless enable standardization of the interfaces in the frequently occurring Connector, an Adapter is used that uses the standardized interface on one side and allows an individual connection to the monument on the other. This creates an additional variant component, but this is overcompensated by economies of scale of the frequently used Connector.

The trunk lid is surrounded by components such as the car body, the bumper and the separated rear lights. However, these neighbouring components only interact with the trunk lid with regard to alignment. Only the hinge shares an interface with it. Along the hinge, there a wire to supply components of the trunk lid with electricity, data and windscreen washer water. All interfaces of the trunk lid body and its mounting parts are detachable, except the interface to the rear window, which is glued to the trunk lid body. The mounting parts are attached with screws and clips. For electricity, data or material flow, components are connected via wires and pipes. These contain connectors at their end, such as plugs and pipe connectors which usually constitute standardized ports. The screws, clips and ports are usually standardized across different industries. However, the interface itself, the contact surface can be variant. Depending on the geometrical complexity of the mating parts, the mating surface – the interface - varies with the geometry of the components. For example, the interface of the rear window and the trunk lid body are variant for each model, due to the three-dimensional bonding flange. In contrast to that, the punctual interface at the screw connection points of the rear

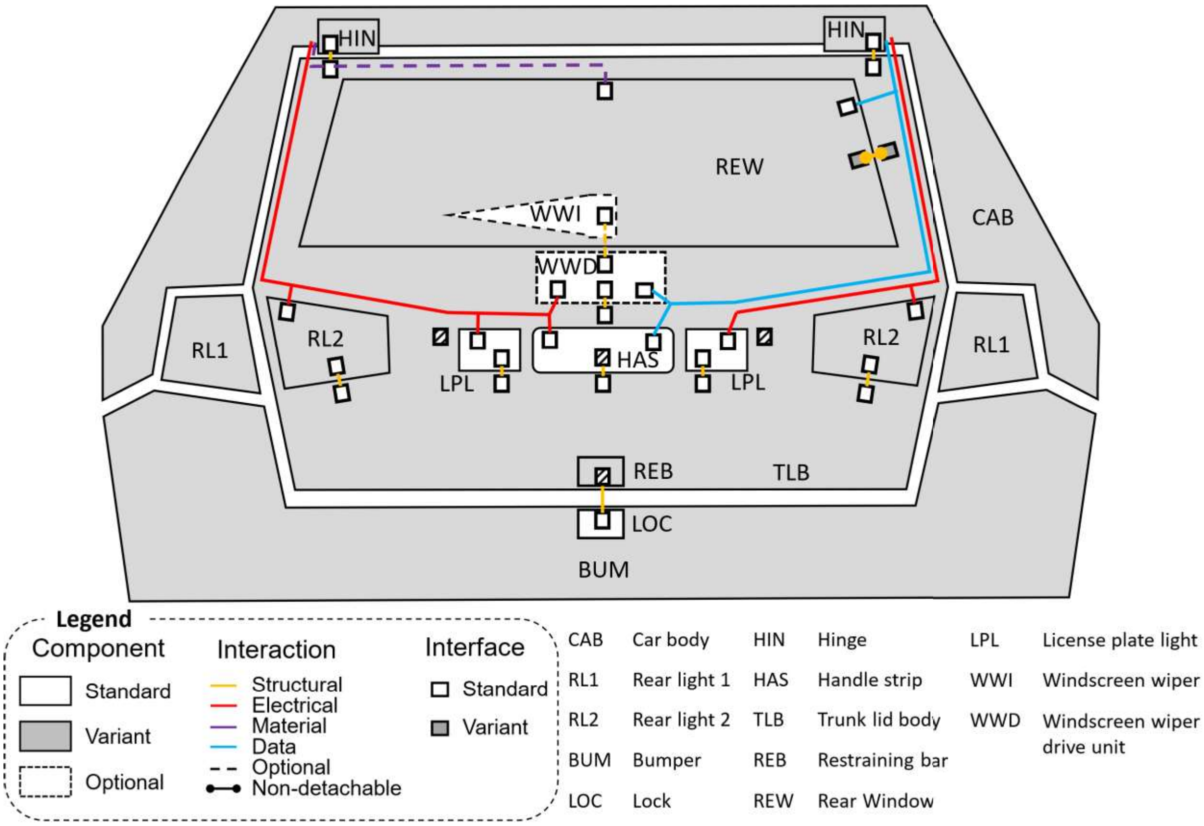


Figure 4: MIG of the trunk lid

light and the trunk lid body is standardized. Thus, rear lights with variant geometrical shapes can be combined with the trunk lid body. The license plate light, which is standardized and used across different car models, contains a standardized clip interface mating a standardized punched hole of the variant trunk lid body. The optional wiper for steeper rear windows of wagons shares an interface with the rear window and its drive unit. The drive unit as an optional component is not supplied with energy and signals via optional wires, but requires an additional variant of the wiring harness. The pipe for the windscreen washer water states an optional interface for the windscreen washer reservoir. Besides product-relevant interfaces, the trunk lid body contains interfaces which are used in the production to open and close the trunk lid with robots or to keep it in position with manufacturing equipment for process application.

5. Discussion

From the perspective of product development interfaces are of crucial importance. They allow simultaneous engineering in adherence to the module interfaces as well as module-wise product modifications. The presented visualization encourages the engineer to rethink the interface design in the context of component variety and module boundaries. As the example of the trunk lid shows, almost all interfaces of the mounting parts are standardized. In combination with the Variety Allocation Model (VAM) which provides further information about the variant characteristics of components, the adapted MIG displays the interfaces of variant components and their mating components to consider the combinability of all variants with regard to the interface. In case of product modification, the visualization of interfaces helps to set the boundaries for redesign and to evaluate the change propagation via interfaces.

Often the internal product variance needs to be mastered by within the production department. However, it is not always the case that product variance necessitates the use of variant processes or equipment in production. As long as the interfaces are standardized or similar regarding joining element and technology, tightening torque and process time, the production can compensate the slight difference in manual work or the robot control. In contrast to that, the Poka Yoke principle is often applied and interfaces are deliberately designed to be variant in order to prevent the incorrect manual assembly of symmetrically identical components.

As the example from the aviation sector shows, the distinction between component variety and interface variety is important, as some of the negative consequences of high variety, such as increased assembly or service costs, only apply to interface variety. The differentiated view allows a focus on the most important product regions in terms of variety and thus enables simplified development. With regard to sustainability, standardization of production-relevant interfaces enables the reuse of production equipment in case of product modifications. Furthermore, the visualization highlights non-detachable interfaces that provide potential for improvement in terms of dismantlability and repairability from the perspective of usage and recycling.

6. Summary and Outlook

This paper highlights the importance of interface visualization in advancing modular product architectures, focusing on the differentiation between standard and variant interfaces. Through the adaptation of the Module Interface Graph (MIG), a robust visualization tool was developed, capturing the essence of both component and interface variety. This visualization effectively illustrates how interfaces can be standardized and strategically varied, allowing for efficient module-wise product modifications. Case studies on the aircraft crown module and car trunk lid demonstrate the practical applications of this approach, underscoring the benefits of standardized interfaces in managing product complexity and enhancing flexibility.

The findings suggest that the standardized visualization of interfaces not only facilitates better product design by clarifying interaction points but also significantly contributes to sustainable product development practices. Such visualization aids in setting clear redesign boundaries, evaluating change propagation, and understanding the implications of detachable versus non-detachable interfaces on product lifecycle management, especially for the repairability and the reuse of modules. The study also shows that the distinction between component and interface variety is important since the negative implications are more significant for interface variance. Consequently, standardization of interfaces also provides benefits for variant components.

Further research can focus on an integration of this visualization tool into existing product development processes, enhancing an optimization of product modularity and enabling easier updates and modifications without compromising on product quality or increasing production costs. This study should focus on the VAM so that the variety of interfaces is adequately taken into account in addition to information on the variety of components.

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