Lifecycle-Oriented Interface Standardization in Modular Product Families: Drivers and Trade-Offs Across Phases

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Abstract

Interfaces play a central role in modular product families, influencing both modularity and cost efficiency. However, their strategic importance throughout the product lifecycle is often underestimated, as the requirements vary largely between different life phases. This paper introduces a systematic approach to identifying, classifying and evaluating interfaces, based on criteria such as functionality, variety, communication effort, lifecycle connection and costs. This approach allows for a relevance ranking and supports targeted standardization or integration strategies. Applying this approach to a robot vacuum product family reveals critical interfaces and related trade-offs, helping to improve product family architectures at an early stage.

Keywords

Product Development, Interface Design, Lifecycle Analysis

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1. Motivation

Interfaces are key elements within product architectures, as they not only define the technical linkages between components but also decisively influence the structure, flexibility, and modularity of product families [1]. Any modification of an interface that exceeds mere alterations in specific parameters, such as bore or pipe diameters, can result in fundamental changes to the product architecture itself [2].

Within the context of product families, managing interface variety emerges as a key challenge. Interface variety refers to the phenomenon in which components serving identical customer-relevant functions are connected via different interfaces across product variants [3]. In the context of a product family, the distinction between product variety and interface variety enables the strategic standardization of interfaces beyond a product variant. [4]. This facilitates the leveraging of synergistic effects in terms of cost and time efficiency across multiple life phases. Concurrently, the challenge arises that the requirements for interfaces are dependent on the perspective of the different life phases.

Despite their significance, interfaces are often treated implicitly in design processes and methodical frameworks. Product development methodologies frequently focus on functional allocation, variant management, or system decomposition, while interfaces remain underrepresented as active design variables[5]. Consequently, there is a growing need for approaches that explicitly recognize interfaces as strategic levers.

Prior to engaging in discussions on standardization, it is essential to identify which interfaces are of strategic relevance. Given that industrial products often comprise several hundred or even thousands of interfaces, it is neither feasible nor efficient to analyze all of them in detail. This consolidates in a lack of established approaches for the classification or systematic identification of the most critical interfaces within a product architecture.

This paper therefore investigates which interface aspects gain relevance across different lifecycle phases and examines the advantages and trade-offs of interface standardization from a lifecycle-oriented perspective.

2. State of the art

The importance of interfaces in product architectures is twofold. Firstly, they establish the functional and structural connections between components and modules. Secondly, they significantly influence the overall performance, cost structure, and adaptability of technical systems. [1], [6]. In modular product families, interfaces are of particular relevance, as they directly affect the configurability, flexibility, and reusability of components across multiple product variants [7]. As such, interface design constitutes not only a technical implementation task, but rather a strategic design decision with ramifications across the entire product lifecycle [5].

A number of classifications have been proposed in the literature to help deal with interfaces systematically. These typically distinguish between functional, physical, and procedural interfaces [1], [8]. Functional interfaces describe dependencies and interactions between functional elements of a system, such as the transfer of signals or energy. Physical interfaces, in contrast, refer to the concrete realization of these dependencies, mechanical fasteners, electrical connectors, or fluid couplings serve as tangible examples. Procedural interfaces describe the organizational or disciplinary boundaries involved in defining or modifying an interface and relate to coordination efforts between departments, suppliers, or development partners [9]. Furthermore, interfaces can be characterized by the type of interaction they support. There are a multitude of classifications [2], [10]. Krause et al. distinguish four primary categories based on the nature of the transfer: force and torque transmission, information transfer, energy transfer, and media transfer [7]. This typology serves as a useful basis for both interface analysis and the selection of appropriate design principles.

Standardization of interfaces is an established strategy for managing complexity in modular product development [11]. It reduces internal variety, fosters the interchangeability of components, and enables economies of scale in procurement, manufacturing, and service. Standardized interfaces allow components to be reused across product variants or generations, and they significantly simplify the implementation of modular architectures [7]. In many lifecycle phases, such as manufacturing or maintenance, standard interfaces yield quantifiable benefits, for example, through reduced tooling variety, shortened setup times, or simplified training requirements.

However, these benefits must be weighed against potential trade-offs. Excessive standardization may constrain the product's differentiation potential, reduce design freedom, or lead to performance compromises, particularly in domains such as lightweight design, where standardized interface dimensions can result in oversizing and increased mass [12], [13]. Accordingly, the degree of interface standardization must be carefully calibrated based strategic priorities.

Interface standardization is considered one of the four key enablers of modularity in product families [14]. Hackl describes modularity as a gradual system property, whereby characteristics such as interface design, functional grouping, and system decoupling can be expressed in varying degrees of strength. [15]. Spallek [16] distinguishes between two forms of interface standardization: intra-variant and cross-variant standardization. Intra-variant standardization refers to the uniform implementation of interfaces within a single product configuration, for example, using a consistent screw type across all subassemblies. Cross-variant standardization, in contrast, aims to harmonize specific interfaces across multiple variants of a product family, thereby supporting the reuse of components in different system contexts. Both forms contribute to reducing complexity and increasing architectural robustness but differ in their scope and implementation challenges.

3. Views on Standardazation of Interfaces

An interface can be characterized either from a technical or a strategic perspective [8]. Technically, an interface establishes the connection between two components to enable a specific form of interaction. The realization of such an interface can be described on three hierarchical levels: the type of interaction, the applied working principle, and the specific technical specification (see Figure 1).

The level of abstraction decreases from left to right in the diagram. As illustrated, an interface enables a defined interaction, which can vary in nature. Accordingly, interfaces may be classified as mechanical, electrical, fluidic, or digital. The interaction defines the mode of transfer, which is physically implemented through a specific working principle. For instance, a mechanical connection may be realized via a screw joint or a clamping mechanism. This working principle is further detailed through technical specifications, such as thread size or screw length in the case of a bolted connection.

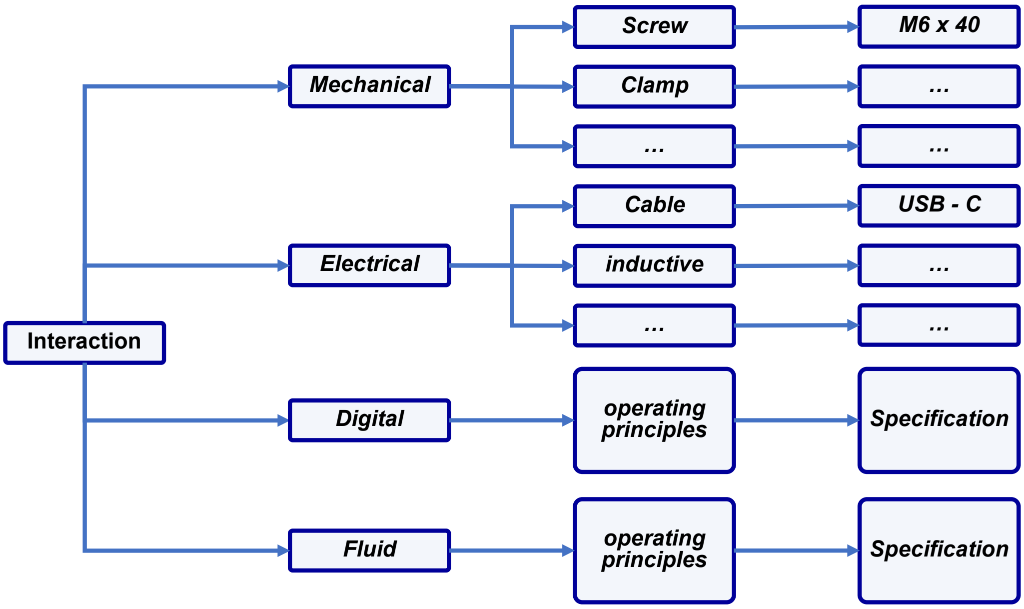

Figure 1: Aspects of the technical implementation of an interface

From a strategic perspective, interface-related design decisions originate at the component level (see Figure 2). Through integral design, multiple functions may be consolidated within a single component, thereby eliminating the need for an interface on the component or module level. Alternatively, differential design introduces additional interfaces to simplify individual components or enable functional decoupling. As a consequence, both standardized and variant interfaces may arise. Interface variety can manifest within a single product or across the variants of a product family. Analogously, interface standards may be defined within a product, across a product family, at the company level, or even across an entire industry.

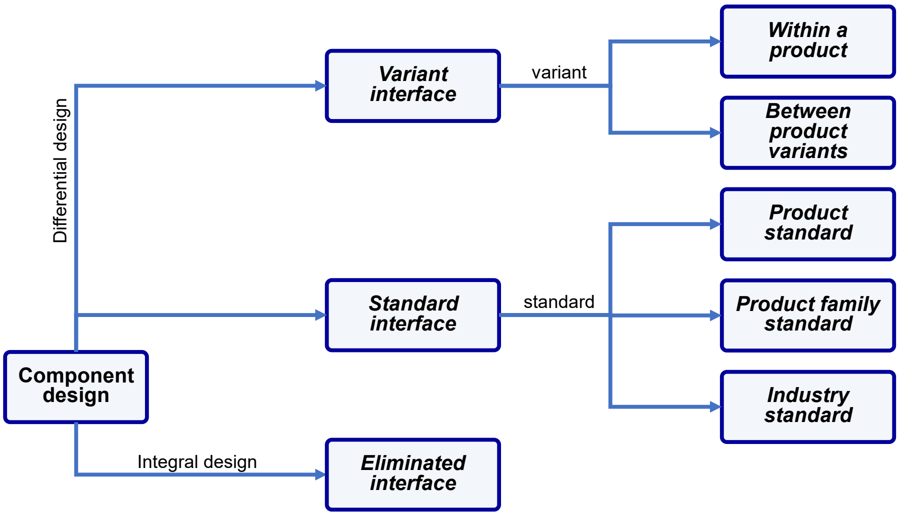

Figure 2: Aspects of the strategic consideration of interfaces

A standardized interface within a single productvariant implies that the same interface configuration is consistently applied on a specific level, such as the interaction level or the working principle level. For example, interaction-level standardization is achieved when all fluidic connections within a product are realized using the same type of coupling. Working principle-level standardization would mean that all screw joints follow a uniform connection principle.

By contrast, cross-variant standardization within a product family does not aim to unify as many interfaces as possible within a single product. Rather, it seeks to harmonize specific interfaces across different variants. Standardization in this context may also take place on various levels. Interface variety across product variants is typically observed on the specification level, for example, in the form of different thread diameters for connector fastenings. However, variety may also exist on the level of working principles, as when upper and lower halves of pressure regulators are joined using screws in one variant and clamps in another.

In analogy to product- and family-level standardization, interfaces may also be standardized at the company or industry level. This is particularly relevant for external interfaces, which enable integration of a product into larger system environments or interoperability with third-party components. Industry standards for mechanical, electrical, or digital interfaces play a central role in this context and often directly affect customer acceptance, regulatory compliance, and market access.

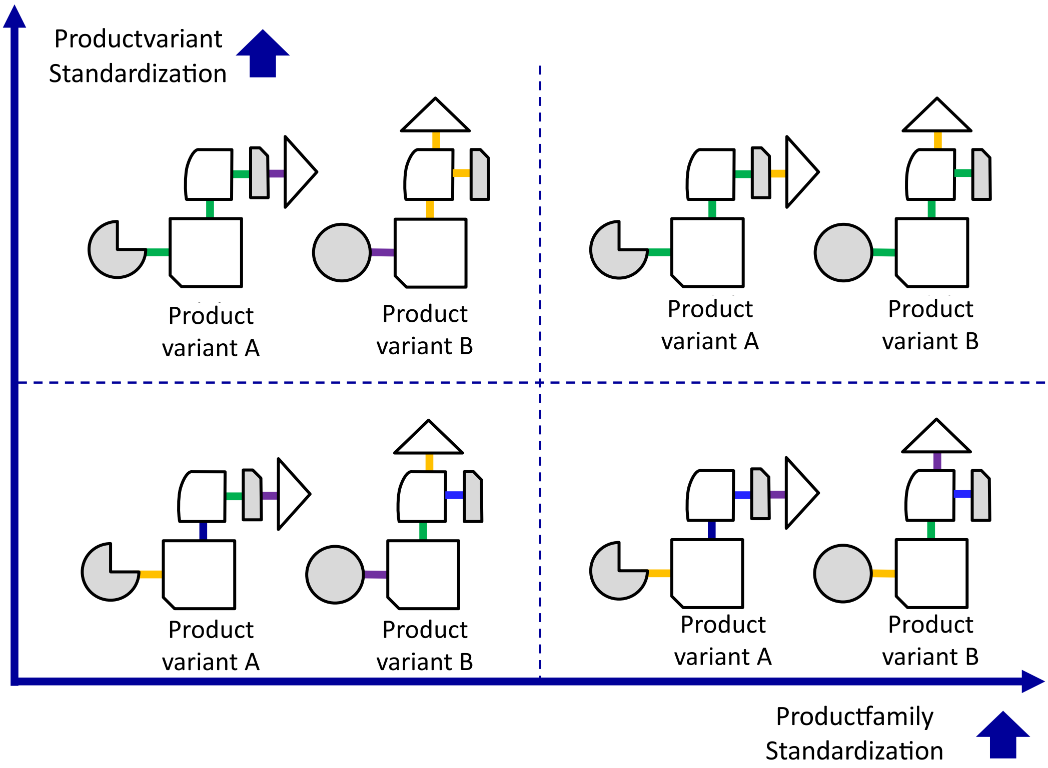

Figure 3: Distinction between interface standardization within a product variant and across a product family

Figure 3 visualizes two orthogonal dimensions of interface standardization. The degree of standardization within a product variant is plotted on the vertical axis. Here, standardization aims to reduce internal variety, for instance, by unifying screw or connector types within a product. This is indicated by the increased number of green or orange connections within each variant. The horizontal axis shows the degree of standardization within a product family, i.e. across several product variants. This is visualized by identical orange connections between the same components in both configurations.

The design and evaluation of interfaces require the integration of both technical and strategic considerations. While technical aspects ensure that interfaces fulfill their functional and structural roles within a system, strategic decisions determine how effectively they support overarching design goals such as modularity, reuse, and lifecycle efficiency.

4. Methodological approach to interface relevance

The proliferation of interfaces in technical products necessitates a systematic approach to narrowing down the range of options, thereby facilitating resource-efficient decisions regarding standardization or integration. In the context of modular product families, it is essential to identify those interfaces that are of high strategic relevance throughout the product lifecycle. To this end, a multi-stage methodological approach is presented that builds on existing classifications and enables cross-phase evaluation.

The methodological approach is centered on the recognition that the requirements for interfaces exhibit significant variation according to the product lifecycle phase. While aspects such as accessibility, interchangeability, and serviceability are particularly important during the use and maintenance phases, time and cost aspects, as well as mountability and process compatibility, dominate during the manufacturing phase. Conversely, in the development phase, aspects such as design freedom, integration potential, and variant management assume particular significance. These differences necessitate the evaluation of interfaces from a perspective that encompasses all life phases, rather than in isolation.

In order to operationalise this perspective, a set of questions was developed, the construction of which was based on five fundamental criteria: *Functionality, Variety, Communication effort*, *Lifecycle connection*, and *Costs*. This approach enables a qualitative assessment of the relevance of individual interfaces within a specific product architecture. The following list comprises examples of key questions:

- *Functionality*: Is the interface functionally relevant or relevant to the safety of the product?
- *Variety*: Does the interface occur in different forms in several product variants?
- *Communication effort:* Are several disciplines or organizational units (e.g., departments/suppliers) involved in the definition, design, or modification of the interface?
- *Lifecycle connection*: Is the interface relevant in several lifecycle phases?
- *Costs*: How high are the manufacturing costs of the components that are connected via the interface?

The questions are evaluated using a binary scale (i.e. yes/no) or semi-quantitative assessment on an ordinal level (e.g. low/medium/high), enabling subsequent weighting and prioritisation. Based on the evaluation, a relevance ranking is created that allows the most critical interfaces within the product architecture to be identified. In combination with the classification by interaction type and system level (see Chapter 3), this provides a structured overview of strategically relevant interfaces. Standardization or integration strategies can then be derived for these interfaces in the further course of the process.

The methodological approach thus consists of the following steps:

1. Identification of potentially relevant interfaces based on the product structure or functional structure
2. Classification of interfaces (internal/external, interaction type)
3. Assessment of relevance based on key questions
4. Creation of a relevance ranking for prioritization
5. Derivation of suitable standardization or integration strategies

This systematic approach makes it possible to understand and use interfaces not only as technical coupling elements, but also as strategic levers for modularity, sustainability, and cost-effectiveness.

To examine the issue of interface dependency on lifecycle phases, a workshop is being held with methodologists from the field of modularization. The advantages of interface standardization will be discussed from the perspective of the lifecycle phases of product development, purchasing, production, sales, use, and end-of-life at different levels of standardization. This has resulted in Table 1

Table 1 Advantages and disadvantages of standardization at different levels from the perspective of different life phases

		Standardization		
		Product level	Product family level	Industry level
Life phases	Product development	⊖ Limited design freedom	⊕ Reuse of modules ⊖ Limited design freedom	⊖ Limited design freedom
	Procurement	⊕ Higher lot sizes	⊕ Reduced coordination time	⊕ Availability of suppliers
	Production	⊕ Repetition of processes ⊖ Higher error potential	⊕ Lower error potential ⊕ Flexible production	
	Sales		⊕ Simpler combinability ⊖ Customer needs alignment	⊕ Low training costs ⊖ Performance limitation
	Use and Service	⊕ Simpler maintenance	⊕ Simpler maintenance ⊕ Upgradeability	⊕ company-independent repair
	End-of-Life	⊕ Simpler product disassembly		⊕ company-independent recycling

At the product variant level, standardization supports operational efficiency through process repetition and facilitates maintenance and disassembly, yet may limit design freedom and increase error potential during production because of missing Poka Yoke principle. Product family-level standardization offers advantages in reuse, coordination, error prevention, and upgradeability, although alignment with specific customer needs may be restricted. On the industry level, standard interfaces promote supplier availability, lower training efforts, and enable company-independent repair and recycling, but can restrict design flexibility and system performance due to fixed external constraints.

The comparison highlights that the benefits and trade-offs of standardization are not uniform but depend heavily on the level of application and the lifecycle phase under consideration. These insights inform targeted standardization strategies based on context-specific priorities.

5. Application of the Approach on a vacuum robot product familiy

To illustrate the application of the proposed method, the brush module of a vacuum cleaner product family from the company RoboVac is examined. The product family comprises four variants that differ in at least one customer-relevant feature. Figure 4 shows the Module Interface Graph (MIG) [17] of the brush unit, which consists of two brushes, a gear unit, a drive motor, and a motor control board. The focus of the approach ist on the key questions.

The first step of the approach is the interface identification. The interfaces are already shown in the MIG (Figure 4), so this step can be considered to have already been carried out. The four interactions of the brush unit with the environment are not considered here, but are also internal interfaces. In the second step, the interfaces are classified. First of all, it can be determined from the product structure that they are all internal interfaces and most interfaces differ in the interaction type.

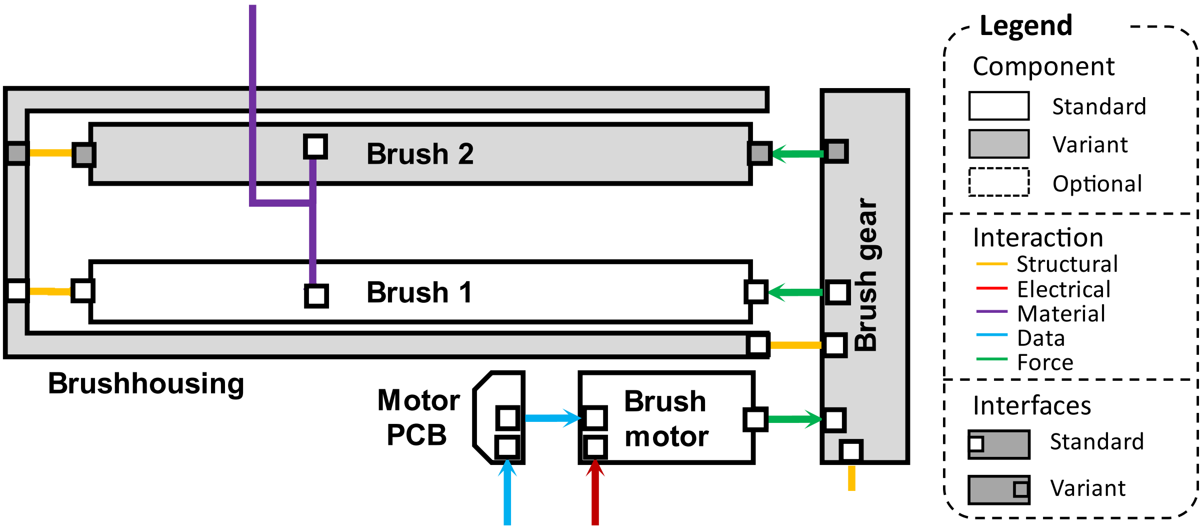

Figure 4: MIG oft he Brush module of a vacuum cleaner product family

In the third step, the interfaces are evaluated using the key questions presented in chapter 4. The results of the qualitative assessment are summarized in Table 2.

Table 2: Summary of the Evaluation of the key questions

Interaction	Functionality	Variety	Communication Effort	Life Phase Connection	Costs
Brush 1 - Brushhousing	Low	No	Medium	High	Low
Brush 1 - Brushgear	Medium	No	High	High	Low
Brush 2 - Brushhousing	Low	Yes	Medium	High	Low
Brush 2 - Brushgear	Medium	Yes	High	High	Low
Brushhousing - Brushgear	Medium	No	Medium	Medium	Low
Brushmotor – Brushgear	Medium	No	High	Medium	Medium
Motor PCB- Brushmotor	Medium	No	Medium	Low	Medium

There are no safety-relevant interfaces for the user in this example. However, almost all interfaces are relevant for the functional performance of the robot vacuum. Only the structural connection of the brushes to the housing is not necessary for functional fulfillment and serves to guide the brush shafts. It can be seen from the MIG that most of the interfaces are standard. Variant interfaces are located between the brush 2 and the housing and the brush 2 and the brush gear. To determine the communication effort, it is assumed that the company is a system integrator and that the parts are sourced as bought-in parts. It is also assumed that both the motor PCB and the brushmotor, as well as both brushes, the housing and the gear are sourced from the same supplier. It can be deduced from this that the interfaces between the brush motor and brush gear and the brush gear and brushes in particular require increased communication effort. The development phase and the purchasing phase are excluded from the consideration of the lifecycle phase relevance, as these are relevant for all interfaces. In the production phase, all interfaces must be joined, apart from the interfaces between the motor PCB and the brushmotor, which may already be purchased assembled. For the sales and service phases, the interfaces on the brushes are the most relevant, as the brushes are wear parts that have to be sold exchanged separately. With regard to the end-of-life phase, non-detachable connections and connections between different material pairings are critical [5]. In the selected example, all connections are detachable, so this is not relevant here. The costs of the components are only evaluated qualitatively here, and the costs of all components are relatively low, with only the brush motor being more expensive than the others.

The evaluation concludes that the connection between brush 2 and the brush gear is the most critical and requires redesign most urgently.

6. Discussion

The identification of critical interfaces within a product architecture represents a substantial challenge. Interfaces have been demonstrated to exert a significant influence on the design of product families. In the context of the modularisation of product families, the standardization and revision of interfaces emerges as a pivotal enabler for enhancing product architectures. The question of which interfaces should be considered when revising product families is addressed here using the approach presented. It has been demonstrated that the significance of interfaces is subject to variation depending on the various stakeholders involved throughout the lifecycle.

Applying the approach presented here to the example of the robot vacuum cleaner shows that critical interfaces can be identified. By integrating criteria such as functionality, variety, communication effort, lifecycle connection, and costs, the evaluation framework enables a differentiated prioritization of interfaces that goes beyond purely technical considerations. The weighting of the various key questions is an open issue that must be discussed with the relevant product experts depending on the objectives. In the example considered, all key questions were weighted equally. It may be beneficial to consider complexity costs in relation to interfaces; however, the process of collecting data on complexity costs is time-consuming [18]. Consequently, the focus has been limited to manufacturing costs for the current study. In the event that data regarding complexity costs is accessible, this should naturally be used.

Standardization could prove advantageous for the critical interface between Brush 2 and the Brush gear, as identified in Chapter 5. However, from a lifecycle perspective, it should be noted that standardising the interface contradicts the poka-yoke principle and could therefore lead to disadvantages in production.

A further limitation is that the assessment is qualitative in nature. The integration of quantitative metrics and indicators has the potential to enhance this approach.

7. Summary and Outlook

This paper emphasises the central role of interfaces in modular product families and highlights their relevance throughout the entire lifecycle. The methodological approach presented shows how interfaces can be systematically identified, classified and evaluated in terms of their significance. Applying this approach to a robot vacuum cleaner product family showed that critical interfaces can be identified and addressed specifically.

The importance of considering the lifecycle phase when determining interface requirements is emphasised, as a one-sided view is insufficient. This approach enables the advantages and disadvantages of interface standardization to be evaluated in a context-specific manner.

This enables efficiency gains and potential limitations, such as those relating to design freedom or production reliability, to be considered at an early stage.

In future research, the qualitative assessment should be supplemented by quantitative indicators to make the basis for decision-making more objective. In particular, taking complexity costs into account could add value. It would also be useful to validate the approach in different industries and product areas to check its transferability and derive industry-specific adjustments.

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