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Enhancing end-of-life sustainability through modularity and interface design in product development

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ABSTRACT: This study highlights the importance of interface design in sustainable product development within a circular economy. By focusing on the end-of-life (EOL) phase, the research emphasizes modular product architectures' role in improving component separability, reusability, and recyclability. An extended Module Interface Graph (MIG) was developed to assess interface variance, detachability, and material pairings, enabling the identification of critical interfaces that significantly influence EOL outcomes. The approach was successfully applied to a portal milling machine, demonstrating its ability to highlight key areas for design improvements, such as transitioning from non-detachable to standardized, detachable interfaces. This method showcases the potential for early interface considerations to enhance both environmental sustainability and product lifecycle management.

KEYWORDS: design for interfaces, sustainability, design engineering, design to x, product families

1. Introduction

In order to enhance the environmental sustainability of products, it is essential to adopt a holistic view, that considers the whole lifespan of a product. However, within this broad framework, the end-of-life (EOL) phase holds significant potential for improvement, as it directly influences material recovery, waste reduction, and the circularity of product systems (Mathur et al., 2023). Therefore, this paper specifically focuses on the end-of-life (EOL) phase, which holds significant potential for improvements. In the European Union, there are multiple regulatory frameworks concerning the EOL phase of products obligating the producers to obtain value from the product at the end of its operational phase (European Commission, 2020; European Commission, 2023). These regulations are aligned with the principles of a circular economy, which aims to close material loops through the implementation of strategies encapsulated in the R-imperatives. These strategies, which include repair, refurbishment, remanufacturing, and recycling, are designed to extend product lifetimes and ensure the retention of materials within the value chain for as long as possible (Reike et al., 2018).

Today's industrial goods are increasingly composed of complex, integral, and multi-material components, presenting substantial challenges for effective reuse within the framework of a circular economy (Jacobs et al., 2022; Tam et al., 2019). One of the critical issues is the separability of components, which affects the feasibility of both reuse and recycling processes. The separability of components is significantly influenced by the product architecture and, in particular, by the implementation of interfaces (D. Krause & Gebhardt, 2023). Poorly designed interfaces can complicate disassembly processes, thereby reducing the economic and environmental viability of reuse and recycling.

In order to facilitate the effective reuse of components in accordance with the principles of the circular economy, it is of critical importance to consider the strategic integration of interfaces from the earliest stages of product development (Wehrend, 2024). By designing interfaces with future reuse and recyclability in mind, companies can reduce waste production significantly and are able to gain valuable resources for production. This early intervention requires strategic planning around interfaces, ensuring that products are not only innovative and efficient during their use phase but components are also viable for future use cycles.

To improve the integration of sustainability principles in product development, this paper investigates the role of interfaces in modularization methods, with a particular focus on their variety and separability in the end-of-life (EOL) phase. The research aims to enhance the consideration of interfaces during the early stages of product development to facilitate reuse, remanufacturing, and recycling, thereby supporting circular economy principles. To achieve this, a systematic analysis of existing modularization methods is conducted, assessing their approach to interface integration. Based on these insights, an existing methodology is extended to visualize and evaluate interface criticality within product architectures.

2. Research background

Product development of sustainable products involves designing and manufacturing processes that minimize negative impacts on the environment while maximizing resource efficiency throughout a product's lifecycle. The phase of product development offers several opportunities for the integration of sustainability principles influencing all stages of a product's life cycle, as this is when the essential product attributes are initially defined (Ponn & Lindemann, 2008).

A number of strategies have been developed to optimize EOL strategies in product development. These strategies address different aspects of sustainability and product lifecycle considerations. Tchertchian et al. (2013) examine the extent of modifications required in the product architecture, emphasizing that effective EOL strategies must align with the degree of integration within a product's design. These strategies encompass a range of considerations, from guidelines on material selection and the minimization of functional and component diversity to environmental impact assessments throughout the product's lifecycle. Furthermore, there exist several relevant design strategies impacting the EOL phase, i.e., design for (dis)assembly, design for (re)manufacturing, and design for recycling. These strategies are often encapsulated under the concept of modular design, which facilitates the separation of components and materials for beneficial EOL treatment.

The concept of modularity has been identified as a fundamental strategy in product development, offering a range of benefits, particularly in terms of enhancing the sustainability of products throughout their entire life cycle (Sonego et al., 2018). A modular product architecture affects all stages of the product life cycle, providing the opportunity to implement sustainable design practices throughout the complete product life cycle (Bonvoisin et al., 2016). In the context of product development, modularity refers to the division of a product into distinct, physically independent modules. This allows product developers to deconstruct complex products into simpler modules (Krause & Gebhardt, 2023). The modularity of a product family can be described by the gradual properties and characteristics of modularity (Salvador, 2007). These characteristics can be directly influenced by the developer, while the aforementioned properties are enabled by the characteristics (Weber, 2007). The characteristics are *Oversizing*, *Interface Standardization*, *Decoupling*, and *Function Binding* (Hackl, 2022). *Decoupling* and *Interface Standardization* directly demonstrate the relevance of interfaces for modularity and thereby also the importance for sustainability. The utilization of standardized components and interfaces within a modular design family allows for the accommodation of diverse product configurations. This adaptability allows for the fulfillment of diverse consumer needs without necessitating a complete overhaul of product lines. Standardization of interfaces can contribute to the reduction of production costs by simplifying manufacturing and assembly processes and significantly reducing effort for maintenance and repair. Products can be upgraded or repaired by replacing only the damaged or old modules, thereby minimizing the need for full product replacements (Umeda et al., 2008). This process enhances the value of the material, as modules that are potentially recyclable can be distinguished from those that are not (Kimura et al., 2001). It is evident that oversizing or a faulty interface design can diminish the efficiency of energy or material interactions, consequently resulting in an intensified environmental impact of the overall product (Durand et al., 2010). Hence, it is recommended that a concentrated effort be made on the interfaces during the product development phase, with the objective of contributing to the creation of a more sustainable product.

In general, an interface is defined as a boundary between distinct areas or as the interaction point between two or more functional elements (Baldwin & Clark, 2000; Ullman, 2010). A clear distinction exists between interfaces and interactions. While interactions denote the input-output relationships between components or modules, interfaces represent the physical or logical area where these interactions occur (Inselmann et al., 2024; Parslov & Mortensen, 2015). The interactions can be further specified according to the transfer, such as mechanical, energy, or information transfers, while the interface can be classified into standard and variant interfaces, as well as fixed and movable connections (Ericsson & Erixon, 1999; Harlou, 2006).

Within this context, Xing et al. (2003) propose ten design guidelines for selecting fasteners to optimize a product's EOL phase. These include the use of standard fasteners, minimizing the number of different fasteners as well as using separate fasteners for reusable or high-maintenance components. However, they mainly focus on product recycling rather than including (partial) reuse and remanufacturing of components. To address these broader considerations, Balkenende & Bakker (2015) have developed design guidelines for products with multiple lifecycles. Their work highlights the influence of interface design on disassembly processes, which in turn affects maintenance, reuse, and recyclability. The design guidelines include recommendations to avoid non-detachable interfaces, utilize standardized interfaces, and limit the diversity of fasteners and the associated tools.

3. Consideration of interfaces within modularization methods

To access the potential of proper interface design for sustainable products this paper follows a structured research approach. First literature research has been performed to identify the utilization of interfaces within existing modularization methods and the corresponding tools. In the second phase an analysis was performed in order to evaluate these findings. Based on the results this paper proposes a novel approach for the consideration and visualization of interfaces within the product development process.

For the literature research a systematic and unsystematic research has been performed. The systematic literature research was based on the areas product development, modularity, interfaces and methods/models. The screening process was conducted in three phases: first, the titles were evaluated; second, the abstracts were reviewed, and third, the full texts were analyzed. The exclusion criteria include medical applications, user interfaces, and human-machine interfaces when the focus is on software implementation, as well as marketing and sales when the emphasis is on market satisfaction, as well as virtual reality. For the unsystematic literature research, a keyword analysis was performed on the identified literature from the systematic research. Based on the keywords snowball research was performed.

For the analysis of the literature seven criteria are evaluated. The first evaluation criteria asses the integration of interfaces within modularization methods. This criterion is fulfilled if the corresponding method considers interfaces on a conceptual or physical dimension and provides methodical support for the consideration. Methods are evaluated as partially fulfilled if the method lacks methodical support for the interface treatment or the consideration of interfaces depends on the method user. The second criteria assesses whether interfaces are visually represented within corresponding tools. Visualization is a crucial element of modularization methods, as it supports comprehending system complexity and facilitating communication across teams. The third and fourth criteria differentiate between the levels at which interfaces are considered. With the fifth criteria a focus is put on the distinction between standard and variant interfaces. Variant interfaces differ across multiple component variant within the product family, while standard interfaces are always the same. The sixth evaluation criteria look into a differentiation between detachable and non-detachable interfaces since this distinction is highly relevant for the EOL phase. Finally, the seventh criterion examines whether interfaces are actively integrated into the module-forming process. This criterion underscores the depth of interface integration and highlights the importance of leveraging interfaces as foundational elements in modularization.

Table 1 presents an extract from the findings of the literature analysis. The extract shows the best regarding the evaluation criteria.

Table 1. Consideration of interfaces within modularization methods

● fulfilled ◑ partially fulfilled ○ not fulfilled	Are Interfaces considered with a methodic approach?	Are interfaces visualized within the corresponding tools?	Are component interfaces taken into account?	Are module interfaces taken into account?	Is a distinction made between variant and standardized interfaces?	Is a distinction made between detachable and non-detachable interfaces?	Are interfaces taken into account in the module-forming process?
(Kim & Moon, 2019)	●	◑	●	●	○	○	◑
(Gu et al., 1997)	●	◑	◑	◑	○	○	◑
(Pimmler & Eppinger, 1994)	●	◑	●	○	○	○	●
(Blackenfelt, 2001)	●	◑	●	○	○	○	◑
(Yu et al., 2011)	●	◑	●	○	○	○	◑
(Stone, 1997)	●	◑	○	◑	○	○	◑
(Blees, 2011)	●	◑	◑	○	○	○	◑
(Gupta & Okudan, 2008)	●	◑	●	○	○	○	◑
(Sand & Watson, 2001)	◑	◑	◑	○	○	○	◑
(Erixon & Ericsson, 1998)	◑	◑	○	◑	○	○	○
(Zamirowski & Otto, 1999)	◑	◑	○	◑	○	○	○
(Harlou, 2006)	◑	◑	◑	○	◑	○	○
(Pakkanen et al., 2016)	◑	○	◑	○	○	○	○

Most modularization methods take interfaces into account, but methodological support for this consideration is sometimes lacking. In numerous instances, the incorporation of interactions is based on the DSM proposed by Pimmler & Eppinger (1994), wherein the interconnections between components are delineated in matrix format. The interaction types of spatial dependency, energy, material, and information transfer are considered, and each is rated on a scale of -2 to +2. However, in addition to the coupling itself, the manner in which this coupling is designed is also of significant consequence with respect to the formation of modules.

In the study by Sand et al. (2002), interfaces are considered by assigning a letter code to the connection type and a coupling strength. This method is therefore more detailed in this respect than the other methods considered, as a physical connection is further subdivided into bolt, groove fit, clip, and pin connections, for example. Stone (1997) also considers the interfaces of the modules or systems in addition to the interactions in the *module interaction list*. Further, a distinction is made between incoming and outgoing interfaces. Kim & Moon (2019) describe a method for eco-modular product architecture. This primarily considers interactions between components and modules but also takes into account the material and service life of components, which has an influence on the EOL phase. The vast majority of methods employ some form of visualization. Such representations may take the form of matrices, block diagrams, or tree diagrams.

In the vast majority of methods, the interfaces are visualized within the corresponding tools. Nevertheless, visualization often only takes place at a conceptual level and only the interaction between components is shown. A concrete visualization of the interfaces in the tools is often not carried out. Furthermore, it can be seen that the distinction between variant and standardized interfaces is not taken into account in almost any of the methods. Only in the method of Harlou (2006) is the distinction made between standard and variant interfaces between organs in the *generic organ diagram*. Harlou (2006) refers to interfaces in this context, but these are better conceptualized as interactions, given that they demonstrate the coupling of two organs. A differentiation between detachable and non-detachable interfaces is absent in all of the methods under examination. This could be due to the fact that the methods consider the products at a very abstract level and the physical implementation of the interfaces is often not considered. In addition, the distinction between detachable and non-detachable interfaces is only of secondary importance in the context of product generation and only becomes more important in the context of EOL.

Nevertheless, the consideration of interface variety and the detachability of interfaces can be useful. Most methods take into account the distinction between variant and standard components. A deeper consideration of the cause of the variety and differentiation between variant components and variant interfaces is useful in order to make the product architecture robust and enhance the product development process.

Considering the detachability of interfaces is particularly important during the EOL phase. The simplicity of the coupling determines the ease with which components or modules can be reused, maintained or recycled separately.

4. Approach for integration of interfaces in design methods

The development of interfaces requires consideration of numerous, sometimes conflicting, influencing factors. This paper focuses on sustainability in the EOL phase, with particular emphasis on separability and interface variety, as these are crucial for the circularity of modular systems. This is founded upon the Module Interface Graph (MIG), as presented by (Blees, 2011) in his work on life phase modularization, where the trade-off between sustainability and other development goals is addressed. In order to achieve this, the MIG is extended to include the representation of interfaces. The representation of interfaces is derived from the illustrations of ports from block diagrams. As part of the extension, the MIG takes into account not only the differentiation of component variety but also the variety of interfaces. This allows for a differentiated variance analysis of interfaces and components. The influence of variant interfaces on the product architecture is greater than the effect of variant components. This is due to the fact that variant components can be integrated via standardized interfaces, which reduces the impact on production, assembly, sales, and EOL. In contrast, modifying critical interfaces has the potential to have a substantial impact on the overall product architecture.

In addition to the variance analysis, the MIG is also extended to differentiate between detachable and non-detachable interfaces, as well as an inclusion of the component material at the interfaces. A distinction between different structural interfaces is visualized in Figure 1.

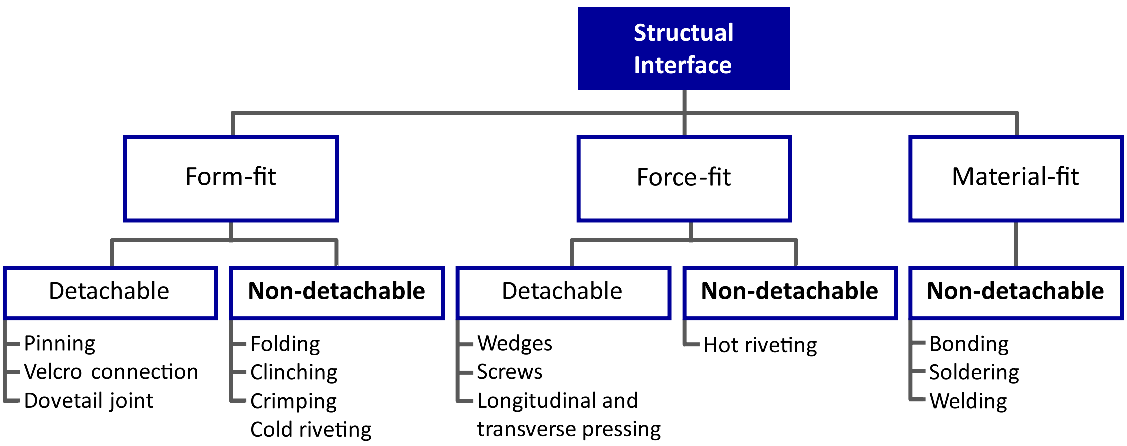
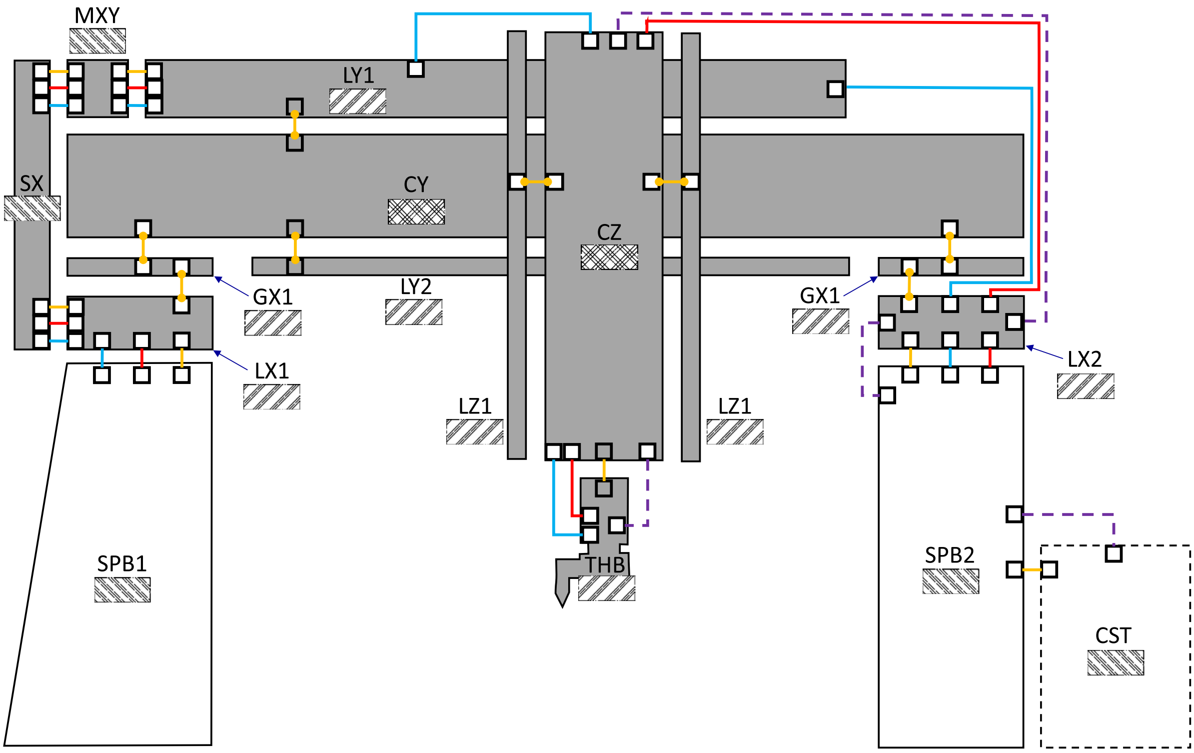


Figure 1. Overview of different structural interfaces based on Risse (2012)

These can be categorized as form-fit, force-fit, and material-fit interfaces. Each category can be further subdivided into detachable and non-detachable interfaces. The figure illustrates that many form-fit connections, such as folding or riveting, are non-detachable. Regarding the EOL phase, the non-detachable interfaces are a particular challenge. In the MIG visualization, non-detachable interfaces are indicated by dots between the interface and interaction. In contrast, detachable connections are represented without dots. This visualization allows for the quick identification of non-detachable interfaces during the development phase.

The visualization of the component materials is based on the principles of tool visualization as described by Gebhardt (2020). An unused visualization dimension in the MIG is hatching, which is now used to represent component materials. The hatching follows the guidelines outlined in DIN EN ISO 128-3

(2022). Since components can include multiple parts and they can have different materials, the hatching always indicates the material used at the interface. To preserve the information about component variance, which is depicted using background color, the hatching is subtly indicated below the component name.
Using the adapted MIG, the most critical interfaces with respect to the EOL phase can be identified. Criticality can be assessed based on characteristics of the interface such as detachability, variance, and the material pairing of the components. This results in different levels of interface types in terms of criticality. An interface is particularly critical if it is variant, non-detachable, and involves heterogeneous material pairings.
Figure 2 shows a representation of the adapted MIG for a portal milling machine.



SPB1	Side Portal Base 1	GX1	Guide Rail Block X-Axis 1	LZ2	Linear Guide Z-Axis 2
LX1	Linear Guide X-Axis 1	LY2	Linear Guide Y-Axis 2	THB	Tool Holder Base
SX	Spindel X-Axis	GX2	Guide Rail Block X-Axis 2	SPB2	Side Portal Base 2
MXY	Motor X- and Y-Axis	LX1	Linear Guide X-Axis 2	CST	Coolant Supply Tank
LY1	Linear Guide Y-Axis 1	LZ1	Linear Guide Z-Axis 1	CZ	Crossbeam Z-Axis
CY	Crossbeam Y-Axis				

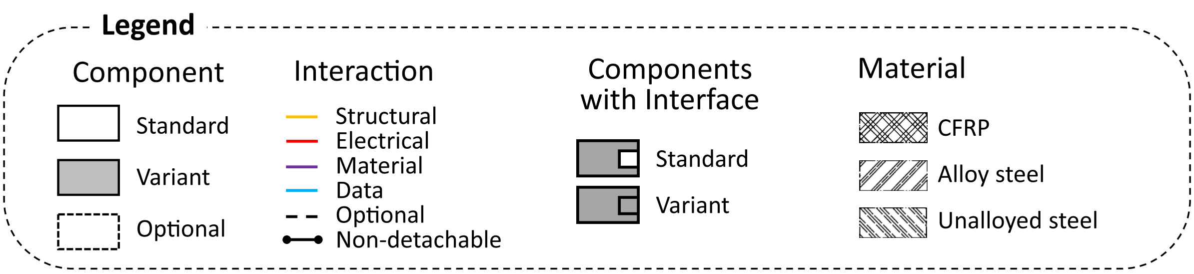


Figure 2. MIG of a portal milling machine extended by interfaces

The figure demonstrates that many of the interfaces of the milling machine are standardized. This applies to all electrical and informational interactions as well as the interfaces for coolant supply. For this milling

machine, the moving axes were replaced with a CFRP crossbeam to reduce the moving mass, which improves the milling quality. The interfaces to the linear guides involve non-detachable interfaces, specifically adhesive bonds. These are standardized for the vertical axis, while for the horizontal axis, they are variant, as different length configurations for the horizontal axis exist, necessitating an extended adhesive surface. Since this is an interface between heterogeneous materials, this results in a critical interface for the EOL phase, which warrants closer investigation to develop alternative solutions. As already stated in Chapter 2 non-detachable interface should be avoided when designing for a product's EOL. Apart from the critical interface identified before there are two more non-detachable interfaces between the linear guide for the x-axis and the guide rail block. The interface is realized as a welded connection. However, as these are made between the same material, the interface is less critical than the previously considered one. The non-detachable connection limits the reuse of the single components, but fewer challenges arise in the recycling process due to the same component material pairing.
Figure 3 illustrates the implementation of the interface between the crossbeam and the linear guide. The upper part of the figure depicts the initial situation, which is also represented in Figure 2. The lower part of the figure presents a proposed enhancement to the interface, with particular consideration to the EOL.

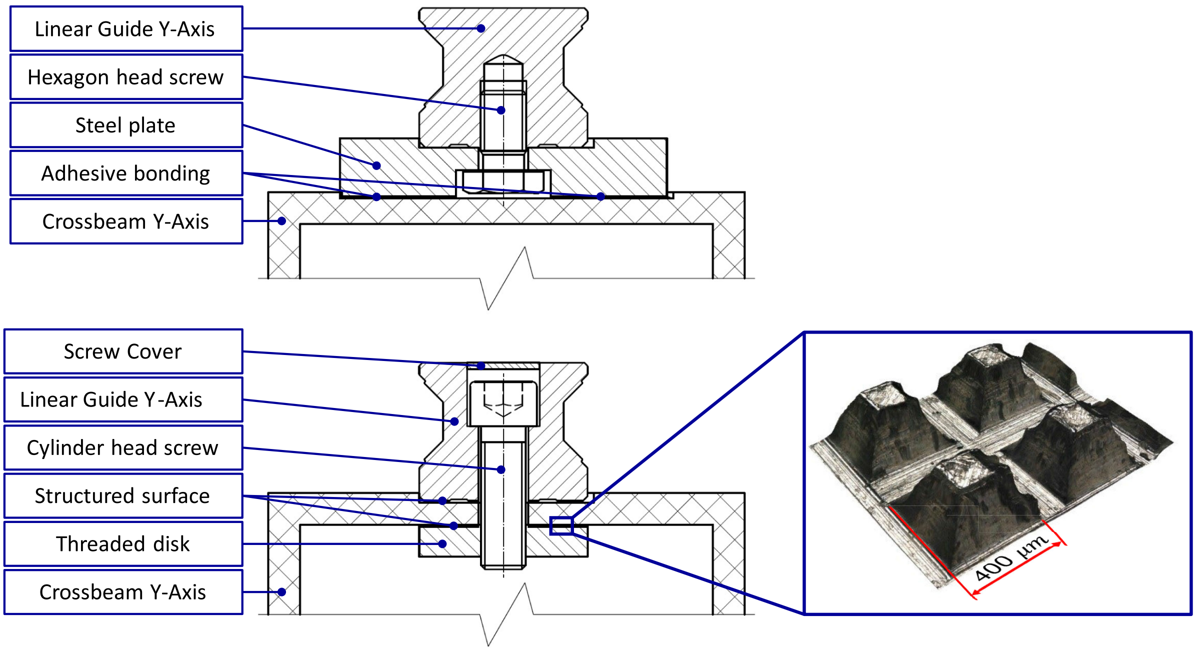


Figure 3. Proposal for interface adjustment

As can be observed in the upper section of the illustration, the linear guide is affixed to a steel plate via screw fastening and which has an adhesive connection to the CFRP crossbeam. The additional steel plate is necessary to achieve the required bonding surface. The lower part of the figure presents a proposal for an enhanced interface design. This is a more technically complex solution, as screw connections in CFRP are often prone to bearing failure. To circumvent this issue, a structured surface is provided, as depicted in the detailed view in Figure 3, which has the potential to significantly enhance the transmissible force (Deutschmann et al., 2024). However, the solution with the screw connection improves the maintenance and repair work that may occur on the part and considerably simplifies the separate recycling of the components. The adhesive bond is stronger than the matrix of the CFRP crossbeams, making mechanical separation of the components very difficult. Consequently, in the initial situation, thermal separation of the components is often the only solution to enable recycling.

5. Discussion

Product development and, in particular, development methods for modular product architectures exert an enormous influence on the EOL phase of products. In particular, the early consideration of interfaces in the development phase allows for significant influence on the EOL phase. The extension of the MIG presented in this paper allows the detection of critical interfaces in the context of EOL optimization in an early development phase. By classifying the criticality of the interfaces, it is possible to prioritize the development of those interfaces that are most relevant in terms of environmental influences. The characteristics of interface variance, detachability and material pairing of the components developed for this purpose have been demonstrated to be beneficial in the context of the milling machine. The materials of the components can only be represented for one material in the current representation. However, as variant components in different versions can also consist of different materials, the form of representation is limited. A possible extension would be to depict the various variant materials in a side-by-side format.

The example of the milling machine interfaces under consideration shows that these have different effects on the EOL based on the characteristics. When considering the EOL, however, a distinction must still be made between extending the product service life, for example through reuse, and recycling.

In principle, the use of standardized interfaces and detachable interfaces is to be preferred. Nevertheless, non-detachable interfaces are frequently employed, particularly in the context of heterogeneous material pairings. This is frequently attributable to the financial implications and the time and effort required for assembly. Examples of this phenomenon can be observed in the case of glued-in car windows or cell phone displays, as well as in the context of metal-fiber composite pairings in aircraft construction. In principle, the majority of non-detachable bonds can also be detached if necessary. This is also frequently observed in repair cases, for example, in which car windows or cell phone displays are replaced. The distinction lies in the fact that the disassembly was not a planned aspect of the product development process and is associated with an increased level of effort required for separation. This results in an increase in time expenditure and, consequently, higher costs. Such additional effort is frequently still undertaken with a view to maintaining the product in the sense of repair. However, when it comes to recycling the products, the increased costs are usually not accepted.

6. Summary and outlook

This paper highlights the critical role of interface design in the development of sustainable, modular products within the framework of a circular economy. Focusing on the EOL phase, it emphasizes the considerable potential for improving environmental sustainability through strategic interface planning. Modular product architectures are identified as key enabler for achieving this goal, as they inherently influence the separability, reusability, and recyclability of product components. An analysis of modularization methods revealed a gap in the explicit consideration of interface design despite its critical importance in aligning with circular economy principles.

To address this, the study proposes an adaption of the MIG. While the MIG was originally developed to represent variance within modular product families, this study enhances it to additionally evaluate and visualize the variance and detachability of interfaces, as well as the material pairing of the components, which were defined as characteristics of the criticality of interfaces. This adaption allows the identification and classification of the criticality of interfaces for the EOL phase and allows to focus the development work on these. The application of this adapted tool to a portal milling machine demonstrated its utility in identifying and improving critical interfaces. Based on the identified critical interfaces in the MIG, it is proposed to replace adhesive bonds with standardized screw connections to enhance component separability, enabling easier disassembly and facilitating the recycling process. These findings underline the environmental and economic benefits of prioritizing standardized and detachable interfaces during the product development phase. The study also highlights the broader implications of these findings. Early integration of interface considerations enables targeted design interventions that align with sustainability objectives while addressing technical and financial challenges. The classification of critical interfaces based on their variance, material pairings, and detachability provides a framework for prioritizing design efforts.

The results of this study highlight that early-stage interface considerations during product development can substantially enhance the feasibility of EOL strategies, supporting both product reuse and recycling. Future research should focus on validating the extended MIG in diverse industrial applications. As discussed in the previous chapter refining the visualization capabilities to represent multiple material pairings could improve the tool. Furthermore, integrating this approach into existing design frameworks and lifecycle analysis tools could amplify its impact on sustainable product development. Future research could be focussed on developing quantitative metrics to evaluate the sustainability impact of interfaces, i.e., measuring the ease of disassembly, providing standardized metrics for assessing interface designs in product architecture.

Another critical aspect requiring further investigation is material compatibility. While it significantly influences component integration, its effect on sustainability has not yet been fully explored. Future research should examine how material compatibility can be systematically considered in the early stages of product development to enhance circularity and optimize end-of-life strategies.

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