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# An Approach Towards Operationalization of Modularization Interfaces for Industrial Product Development

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**Abstract.** The specification of interfaces is critical in modularization and product architecture development. Literature defines product architecture as (1) the arrangement of functional elements, (2) the mapping from functional elements to physical components (3) the specification of the interfaces between interacting physical components. However, other scholars state that interfaces should include more than physical components, such as spatial, material, energy, and information exchange. This view has been extended to include attachment, transfer, control and communication, power, spatial, field, and environmental interfaces. However, to use interfaces through the product lifecycle and reuse them between product architectures and generations, there must be an approach to handle applicable interfaces in a company. This research contributes by presenting a way to operationalize (investigate an abstract concept, it's essential to make it measurable and tangible) interfaces by introducing interface requirements that are definable, measurable, definable, and testable properties as a part of the interface development process and interface description. The method is illustrated by applying it in an industrial case study.

**Keywords.** *Modularization, product lifecycle, product architecture development, operationalization of interfaces, product development*

## Introduction

The specification of interfaces is critical in modularization and product architecture development. Product architecture can be defined as (1) the arrangement of functional elements, (2) the mapping from functional elements to physical components (3) the specification of the interfaces between interacting physical components [1]. However, interfaces have to cover more than the physical connection between components, as proposed by [2]. Here, four types of interfaces are defined: spatial, material, energy, and information (cf. section 2). In the context of smart connected products [3] or quantified products [4] that are characterized by a high integration and interaction between physical and intangible elements, such as software and services,  the characteristics of interfaces has to be further extended, which has been add addressed by Bettig and Gershenson [5].

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Moreover, modularization and the interfaces between modules has been emphasized as an important component in the product lifecycle [6].

In the light of increasing product complexity due to the developments mentioned above, we argue that the importance of interfaces in combination with a systematic operation strategy grows as part of the product lifecycle.The role of interfaces as enablers for both smart products and for the circular economy highlights the need for a structured approach to manage them in practice in a company. To develop products for the circular economy, in the aspects of upgrades, facilitated repairs and planned recycling, it is crucial to manage interfaces through the product lifecycle and to reuse them between product architectures and generations.

The aim of this research is to contribute to improved efficiency in the product lifecycle by presenting a way to operationalize interfaces by introducing definable, measurable, and testable properties as a part of the interface development and description.

The main research question for the paper is: What could be a suitable way to make interfaces operational for complex products?

Based on an analysis of realted work (section 3) and own experience in industrial modularization projects [7], the paper proposes a framework for operationalization of interfaces in industrial product development (section 4). The approach is illustrated by applying it in an industrial case study (section 5). Section 6 discusses conclusion and presents future research.

## 1. Research Methodology

The research approach used combines a literature study and a case study. Since the literature study showed a gap between industrial practice in interface design and state-of-the-art research, we also studied a case of modularization development (section 4). The case study in this paper are exploratory [8], as they are used to clarify interface design in the product life cycle. Based on the case study material and the related work, we propose a customer centered engineering process in the context of modular product design. Furthermore, as one of the authors in this paper has been actively involved in the case, we can extract and reconstruct empirical data from his experiences and case documentation. Also, a key project member was interviewed to capture a longitudinal understanding of how the proposed work with interfaces has facilitated the introduction of new modules.

The related work relating modularization was found using the search string (product AND "product design" AND (modularization OR modular OR modularity) AND interface), which resulting in 297 articles, where 60 articles were elaborating on different modularisation methods and how to handle interfaces. The essential results of this analysis are described in the next section. The full content of the analysis is available in [7].

## 2. The role of modularization and interfaces in product development

The role of modularization for a sustainable product architecture is described by Bonvoisin et al. [9]. The development of a sustainable product architecture is based on the identification of modules, the design of modules and design with modules, e.g. the combination of modules into a specific product variant. From a lifecycle perspective, modularisation enables a faster creation of new product variants [10] as well as significantly reducing the time and resources needed to develop their corresponding manufacturing system [11]. A crucial step is to specify the interfaces between interacting modules [1]. Blees et al. [6] further emphasize the interfaces as enablers for the complete product lifecycle so that manufacturing considerations, recycling, and supplier interaction regarding active or passive module sourcing is considered in when defining interfaces.

The traditional focus of interface definitions is on physical objects and the geometry between physical components. However, interfaces also describe other types of interaction. Steward [2] defines four classes of interfaces: spatial – physical relationship between two modules, material – transfer of materials between two modules, energy – transfer of energy or power between two modules (including interactions in which force-type quantities react between modules without energy being exchanged e.g., force without motion, voltage without current, pressure without velocity), information – transfer of information or signal between two modules. Interface types are further elaborated by [5], who define seven interface classes: Attachment interface – how one component is physically connected to another, Transfer interface – how power or media is transferred between components, control and communication interface – how the state of one component will be communicated to and/or controlled by other components, Power (electrical) interface – how electrical power is transferred between components, Spatial interface – The spatial location and volume a component may occupy, Field interface – Various ways in which the functioning of one component may generate heat, magnetic fields, vibrations or other environmental effects that must be accommodated by other components. Environmental interface – The ambient climate environment where the component must operate and function.

Several scholars have recognized the importance of interfaces in modular development through the whole product life cycle, across time and product families [12,13,14] To consider different types of interfaces, Blees et al. [6] has for instance suggested a method for concept development based on functional decomposition, variant analysis, interface analysis and product lifecycle analysis, see Fig. 1 and description below. Interfaces are described graphically for the product in a Module Interface Graph [6]. For the lifecycle of components, interfaces that must be adapted to enable purchase, production, sales, use, and replacements/repairs of specific modules are highlighted.

An important step in defining the goals and requirements that drive modularization projects is the anaylsis of the business case [7]. Few articles consider the connection between a business case and the modularization strategy. Recent studies show that products with a substantial part of value creation originating from built-in IT components or connected IT services, such as smart connected products, might require adapted modularization strategies and interface definitions. The Internet-of-Things (IoT) and digital transformation has since long become reality of many industrial domains and the innovation of business models [15]. Many physical products are equipped with sensors, control units and actuators that allow for monitoring and controlling them via Internet [4] . Smart connected products are not only a category of IoT products but also represent a business model category characterized by IT- and data-based services [3]. Lately there is even a development towards quantified products [4], where the trend is to quantify the products by (a) collecting data not only from a single device but the entire fleet of products operating in the field, (b) using this data for monitoring and real-time control in a digital twin of the fleet, and (c) offering aggregated data on marketplaces. This trend towards quantified products is accompanied by substantial changes in the companies product lifecycle management. This is an important aspects that also need to be catered for during modularization in the product lifecycle.

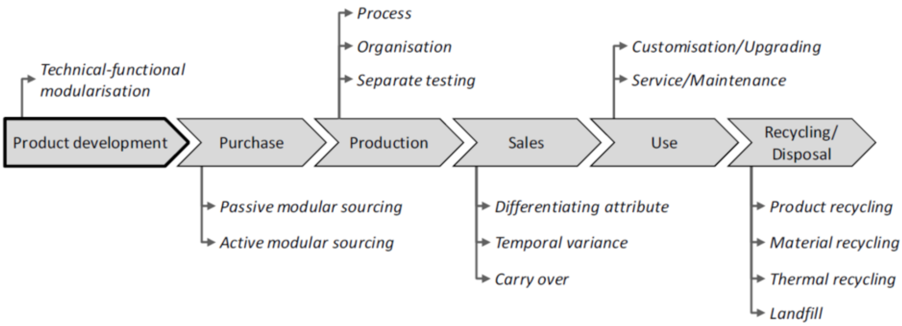



**Figure 1.** Module drivers allocated to product life cycle phases. After [6].

The initiation with a business case is also missing in other frameworks that develop support for the whole product lifecycle. Otto et al. [16] presents a 13-step method starting from market and customer needs, but the business case is missing. In the MFD (Modular Functional Deployment) framework, Erixon [17] discuss the importance of conneting modules to different business objectives, but do not really show how it can be achieved.

To conlude the discussion, there is a need for better ways to define and design interfaces in modularization. Furthermore, since interfaces are an integral part of modularization, interfaces must also be in alignment with the business case. Without a clear aligment with the business goals, product-strategic modularization is not possible [7] and the resulting modular system will not reach its full potential.

## 3. A framework for operationalization of interfaces in industrial product development

This paper presents a framework for operationalization of interfaces in industrial product development that is supposed to cover the whole product lifecycle. The main focus is the management of interfaces, which is not well described in the literature. The proposed framework begins with creating the business case, as discussed in Lennartsson et al. [7] to determine the economic potential for a suggested modularisation concept. To get the full effect of modularization, a product strategy is needed, where the character of each module is defined; e.g. which modules that can be reused from previous products, which new modules that need to be developed and which need to be provided by suppliers. Both the business goals and product strategy will affect the number of modules and interfaces, and must be developed iteratively together in a transdiciplinary approach.

The paper therefore suggest a new way to manage interface design that also include performance steps and technical solutions. The paper introduces the Interface Design Matrix (IDM) and suggests a new A3 interface documentation inspired by the template presented in [18] and used throughout the product life cycle.

To manage interface design, the following CCEP (Customer Centered Engineering Process) is proposed: A five-step process used throughout the product life cycle, Fig 2.

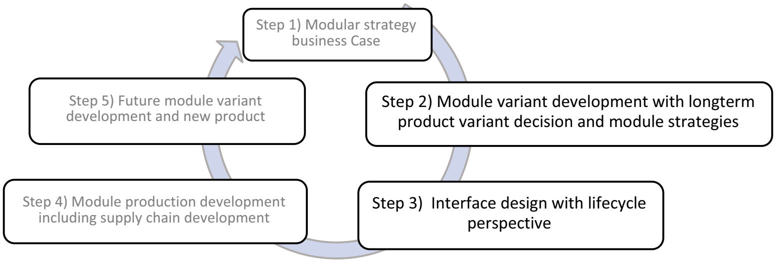



**Figure 2.** Customer Centered Engineering Process (CCEP). The focus of this article is Steps 2 and 3.

Due to space limitations we have choosen to limit the elaboration of step 1 in this paper, but step 1 is deeply described in Lennartsson et al. [7] and we have taken the consequences of step 1 in our elaboration on step 2 and 3.

**Step 1) Modular strategy business Case**

The process starts with the development of a business case that includes a modularization strategy with metrics. To translate customer values to product properties, QFD (Quality Function Deployment) [19] is used. In QFD, these properties are not defined by goal values, but the result is a translation from customer values to product properties. QFD is the handshake between product owners and system engineers regarding the goal of the product family. It acts like a motor that drives the whole customer engineering process. First, it highlights the ranking and importance of the defined properties. Second, it steers the succeeding development work to realize the identified product properties.

**Step 2) Module variant development with product variant decisions and module strategies**

Module variant development is derived from product properties by adding defined goal values and is documented in the MSM (modular system matrix). Modules, module variants, and components are suggested from a functional decomposition into a required module architecture. The goal is to arrive at a module architecture that contains enough variety to fulfill the current customer needs and to be prepared for future upgrades, Fig 3. Furthermore, the literature indicates that this activity is possible to support with different tools, and Johannesson [20] presents software to create the module division.

**Step 3) Interface design with a lifecycle perspective**

One enabler for a sustainable product life cycle is the interface strategy and development. In the interface strategy/development matrix, the starting point is to identify the technical solutions in the interface between the modules. Then, interface dimensioning properties and interface drivers will determine how many interfaces that are needed for the specific interface. It is vital to create as few interfaces as possible.

If there are too many interfaces, the process will go back to the MSM of step 2 to check the opportunity to reduce the number of variants or redesign the module. Finally, the interface is defined in a standardized way using an A3 [18] as a shared documentation for the whole product life cycle, including planned product upgrades and recycling.

The literature also shows that operationalizing an interface design is not straightforward to manage. Interface design and documentation need attention [5]. The literature and empirical conclusions from different industrial cases show the following. First, interface analysis with interface variant reduction enables the configuration of different products [5] (Step 3). Documenting interfaces as a separate document [5] is also essential (Step 3). In the literature, the operationalization of interfaces in industrial product development is mentioned but not shown how to actually do it. (Step 3). It's also important to design interfaces for the whole product life cycle and make the interface robust over time, this will be especially important for complex products. (Step 3- 5).

Interfaces are also important as a mean in a circular economy; for example, with a good interface, a car battery can be used three times: in the car, in houses for the second owner, and for material recycling. Therefore, it is crucial to plan for repair/replacement/upgrade of critical modules (steps 1- 5). Product quality also depends on robust interfaces in order to isolate the modules to be redesigned. In this way, the new design is not affecting other modules. Isolated modules also enable independent testing in development and production to ensure product quality and customer satisfaction.

Interfaces for reducing downtime will also be of vital nature. If an interface is designed so that a module can be replaced with minimal disturbance in ongoing production, usage and to be repaired offline, it contributes to decreasing downtime. Repaires done offline can also enable higher repair quality and less waste of expensive parts or raw materials due to less time pressure on the repairer.

**Step 4) Module manufacturing- and supply chain development**

In module manufacturing development, an advantage is to create module areas and module manufacturing, making it easier to relocate the manufacturing set up to other production facilities without quality problems. In addition, the tools of Make or Buy and Low-cost country evaluation and supply chains can be used for evaluating each module in the external supply chain.

**Step 5) Future module variant development and new products**

Based on the previous steps future development of properties can be foreseen and included for future module variants (steps 1- 5). This includes reusing parts in new products, developing new module variants, and if needed, a few new interfaces with customer input. The circular economy and smart products will be handled in the modularization strategy in the first step. Also, planned future product variants will be documented and prepared in the IDM (interface design matrix), which is the strategy and development matrix used to share and develop knowledge (Step 3).

## 4. Industrial case: Modularization of train coupler

The work presented in this paper builds on the case presented in the paper by Lennartsson [7] which describes a modular strategy, modularization method, and the corresponding metrics. It is a case of product development within the train business. This paper describes an extension of the MFD process that develops modularization metrics and interface variant documentation, which is crucial for the practical implementation of interface design.

In this paper, the focus is on interfaces. The first step of the CCEP is to understand the business case and modularization strategy [7]. In this step, the circular economy work is actually initiated, but the enabler is the development in steps 2 and 3. In step 2, the development of MSM is done. Fig 3 shows the MSM matrix with module variants for a train coupler. All properties are derived from the QFD, and goal values are added to describe the product variants. In the rightmost marked column in fig 3, it is possible to see the different module variants that come from properties with goal values.

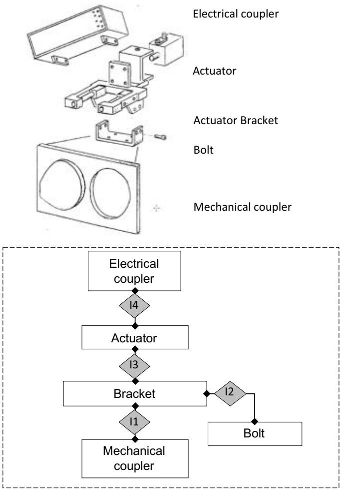
| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | | Control | | | | | | | | | | |
| 2 | | Shielded | 3 | | 120 | | | 29 | | Semi-permanent | Electrical coupler contact device | |
| 1 | | Coax | 2 | US | 100 | | | 36 | Simple | Automatic hook | Mechanical coupler | |
| 0,25 | Housing | Power cables 35 mm2 | 1 | EU | 80 | 75 | 100 | 48 | Weather proof | Automatic latch | Coupler control | |
| Hours | Protection type | Type of signal | Size | Standard | Ohm | Ohm | Amp. | Size | Type | Coupler type | Module | |
| Traffic down time | Environmental protectio | Signal variants | Covers for signals | Control ignal Standard | Shielded level | Coax signal | Power signal | Cable hoze size | Quick connectors | Type of coupler | Heaters for modules | **Modules** |
| | ● | | ● | | | | | | | | | Electrical Coupler Housing |
| | Housing | | 1 | | | | | | | | | Electrical Coupler housing size 1 |
| | | | 2 | | | | | | | | | Electrical Coupler housing size 2 |
| | | | 3 | | | | | | | | | Electrical Coupler housing size 3 |
| | | ● | | ● | ● | ● | ● | | | ◑ | ◑ | Electrical coupler contact device insulating block |
| | | Control | | EU | | | | | | Automat latch/ Semi permanent | Electrical coupler contact device | Electrical coupler contact device latch insulating block control signals control wires 2,5 mm2 europe heate |
| | | Control | | US | | | | | | Automat latch/ Semi permanent | Electrical coupler contact device | Electrical coupler contact device latch insulating block control signals control wires 2,5 mm2 US heater |
| | | Shielded | | | 80 | | | | | Automat latch/ Semi permanent | Electrical coupler contact device | Electrical coupler contact device latch insulating block shielded signals shielded wires 80 Ohm heater |
| | | Shielded | | | 100 | | | | | Automat latch/ Semi permanent | Electrical coupler contact device | Electrical coupler contact device latch insulating block shielded signals shielded wires 100 Ohm heater |
| | | Shielded | | | 120 | | | | | Automat latch/ Semi permanent | Electrical coupler contact device | Electrical coupler contact device latch insulating block shielded signals shielded wires 120 Ohm heater |
| | | Coax | | | | 75 | | | | Automat latch/ Semi permanent | Electrical coupler contact device | Electrical coupler contact device latch insulating block coaxial signals coaxial signals 75 Ohm heater |
| | | Power cables 35 mm2 | | | | | 100 | | | Automat latch/ Semi permanent | Electrical coupler contact device | Electrical coupler contact device latch insulating block power signals signals power cables 35 mm2 100 A h |
| | | | | | | | | ● | | ◑ | | Electrical coupler contact device latch cable hose |
| | | | | | | | | 48 | | Automat latch/ Semi permanent | | Electrical coupler contact device latch cable hose size 48 |
| | | | | | | | | 36 | | Automat latch/ Semi permanent | | Electrical coupler contact device latch cable hose size 36 |
| | | | | | | | | 29 | | Automat latch/ Semi permanent | | Electrical coupler contact device latch cable hose size 29 |
| | | | | | | | | | ● | ◑ | | Electrical coupler contact device latch connectors |
| | | | | | | | | | Simple | Automat latch/ Semi permanent | | Electrical coupler contact device latch connectors low budget " indoor use" |
| | | | | | | | | | Weather proof | Automat latch/ Semi permanent | | Electrical coupler contact device latch connectors quick type "litton or HTS" |

**Figure 3.** Module System Matrix (MSM) for the electrical coupler system in the Train coupler.

## *4.1. Identifying the right level of module breakdown for operationalizing interfaces*

The MSM matrix makes it possible to see the modules connected to properties. Here, a filled circle defines one module variant for each goal value, a half-filled circle to cover a few goal values with one module variant, and an empty circle when one module variant can fulfill all goal values. If the module is connected to several properties, approximately 5-10 connections, a further decomposition of the module is necessary to avoid unnecessary variants. It is possible to see the different strategies for different modules in column W. For example, mechanical couplers have process and organization because additional manufacturing operations are needed when a defect is detected in the coupling surface after machining. Coupler control needs to be developed by a supplier because of a lack of in-house competence. The center section needs a new variant that is not yet developed, indicated by a blue color in the goal values for the planned module variant gas hydraulic double-acting damper. The spacer adapts the new train coupler to old designs, which is required to adjust the coupler's length and reuse of mechanical coupler. The mechanical coupler needs new variants for the US market, a Hook type.

Furthermore, configuring a new product is done the same way as for submodule to a module in fig 3, where it is possible to see submodule variants configured to module variants. In step 3, the interface design is done using an IDM (Interface Design Matrix) that describes an operationalization of an interface and how to analysis the interface. In fig 4, it is possible to see how to follow up the design for the whole product life cycle. In the IDM, properties from MSM drive the specific interface design for the product life cycle. For example, in figure 4, it is possible to analyze the interface between the electrical coupler system and the mechanical coupler. To have an expanded view of the interfaces make it easier to study. Also, a configuration map for submodules configured to a module is vital to understanding the interface. An example of a modular description with interfaces is shown figure 4, and to do this in a structured way, the starting point is the MSM and the product configurations that comes from customer needs and the analysis of the most critical interfaces.




| Sub modules | Electrical coupler module variant 1 | Electrical coupler module variant n |
|---|---|---|
| Electrical Coupler Housing | | |
| Electrical Coupler housing size 1 | | n |
| Electrical Coupler housing size 2 | 1 | |
| Electrical Coupler housing size 3 | | |
| Electrical coupler contact device insulating block | | |
| Electrical coupler contact device latch insulating block control signals control wires 2,5 mm2 europe heater | 6 | n |
| Electrical coupler contact device latch insulating block control signals control wires 2,5 mm2 US heater | | |
| Electrical coupler contact device latch insulating block shielded signals shielded wires 80 Ohm heater | | |
| Electrical coupler contact device latch insulating block shielded signals shielded wires 100 Ohm heater | | |
| Electrical coupler contact device latch insulating block shielded signals shielded wires 120 Ohm heater | | |
| Electrical coupler contact device latch insulating block coaxial signals coaxial signals 75 Ohm heater | | n |
| Electrical coupler contact device latch insulating block power signals signals power cables 35 mm2 100 A heater | 2 | n |
| Electrical coupler contact device latch cable hose | | |
| Electrical coupler contact device latch cable hose size 48 | | |
| Electrical coupler contact device latch cable hose size 36 | 8 | n |
| Electrical coupler contact device latch cable hose size 29 | | |
| Electrical coupler contact device latch connectors | | |
| Electrical coupler contact device latch connectors low budget " indoor use" | | |
| Electrical coupler contact device latch connectors quick type "litton or HTS" | 8 | n |

**Figure 4.** Modular description for electrical coupler system.

In figure 5, it is possible to see the interface design with a life cycle perspective which includes both the IDM and interface design status. In this practical example, no additional interfaces are needed to handle the different interface driver's goal values for mount direction, forces, etc.

It is also possible to change the electrical coupler in 15 minutes by losing four screws so the train can be used quickly after a service stop. The purpose is to develop support to handle different module variants and design interfaces. Also, reducing interfaces is in focus. The goal is to keep the interface design unchanged for the whole product lifecycle. Finally, it is critical to know how far the design has reached for the entire product lifecycle, which can be done with marks like red, yellow, and green, see fig. 5.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Topmounted | Level 3 | | 2 | | |
| | | Side mounted right | Level 2 | | 1 | | |
| Interface design matrix | Goal values | Side mounted left | Level 1 | Easy to demont | 0,15 | | |
| | Units | Mount direction | Forces | Recycling | Hours | | |
| **Interface dimensioning properties** | **Interface drivers** | Mount direction | Forces | Recycling | Traffic down time | Interface concept Proposal | Future interface variant US market |
| **Interface** | | | | | | | |
| I1.a | | 1 | 1 | 1 | 1 | 1 | 1 |
| I1.b | | 1 | 1 | 1 | 1 | 1 | 1 |
| I2 | | | 1 | 1 | | 1 | 1 |
| I3 | | | 1 | 1 | | 1 | 1 |
| I4 | | | 1 | 1 | | 1 | 1 |
| Resulting interface variance | | | | | | | 2 |

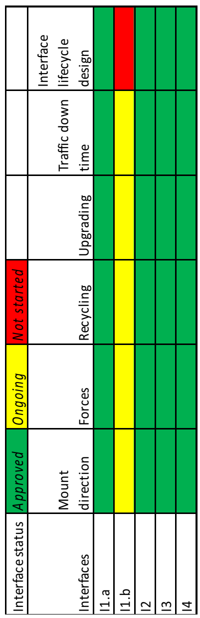



**Figure 5.** Interface design with a lifecycle perspective.

Future development is a new development of Hook-type mechanical coupler for the US market, which can give a new interface.

The train coupler has been extended with a new module after the end of the described modularization project to illustrate further the strength of having structured interface descriptions for a complex product. In addition, by using the same interfaces, a new module has been introduced that can detect exactly which part of the coupler needs to be changed after a crash.

### *4.2. Design of interfaces*

The practical design of interfaces is done as a part of the detailed product development. The IDM is a specification that supports the detailed design of the interface. The IDM has three functions: firstly, it documents the analysis of the interface. Secondly, it specifies the number of interfaces to prepare for detailed design. Finally, it manages current and future module variants connected through the interface by showing the development status in the product life cycle.

## 5. Discussion and future research

For the research question *What could be a suitable way to make interfaces operational for complex products?*, it is possible to see that it supports the development and definition of interfaces in the case study. Regarding the generality of the approach, the train coupler product family is a complex mechatronical system that consist of more than 3000 individual parts, so the approach should be applicabe to other cases of the same transdisciplinary character. However, more cases are needed to answer the research question entirely.

The research underline the importance of designing robust interfaces that are valid throughout the whole product life cycle, thereby enabling product upgrades, facilitating repairs and planned recycling, which is important for the circular economy. In the presented case, new functionality was also added in a new module that detect which part of the coupler needs to be changed after a crash. Future development of properties is therefore possible, with minimal impact on the product, if the required goal values for future module variants are considerd in the interface design.

With this example it is possible to illustrate how the presented framework can cater for well planned interfaces which can facilitate future development of complex products. Another important aspect is that product quality also depends on the ability to isolate the module, which requires robust interfaces. This enables independent module testing in manufacturing, as well as the possibility of using designed interfaces for complex and smart products as described above in the article.

The interface requirements are used for detailed desing of modules and interfaces and are documented in a compact, standardised A3 format that is shared and developed iteratively as the module variants are refined in the Modular System Matrix.

For future research, it may be possible to use the Configure Component Modeler tool [20] for functional modeling and also use the same tool to create a module system profitability tool.

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