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Effects of Product Personalization: Considering *Personalizability* in the Product Architecture of Modular Product Families

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The modularity of a product architecture with standard, variant, and optional modules can be measured by the characteristics of commonality and combinability. Positive and negative effects of a more communal or more combinable structure are summarized and visualized in an impact model. However, due to the megatrend of personalization, the solution space of a modular product architecture needs to be extended to include personalizable modules. What remains unclear till now is how personalization impacts the different life phases. Therefore, this article derives an impact model considering product personalization. First, the modularity property of personalizability is derived, in order to then specifically investigate the effects occurring in the different life phases. Therefore, a literature review is conducted. New effects are found, and the existing effects of commonality and combinability are examined for their validity for personalizability. The findings are then combined with the known effects of commonality and combinability to create a holistic impact model of modular product families. This new model takes personalizable modules into account and can support companies in defining the goals and focus of a modularization project.
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1 Introduction

Using modular product families, companies can find a compromise between the external variety of products demanded by customers and the internal variety that arises within the company [1–3]. For this purpose, modules are combined with each other to form product variants. Modules can be standardized and used commonly across several product variants or, if necessary, also across product families [1,4]. Furthermore, modules can be variants and give the corresponding product variant of a product family its characteristic properties [4–6]. In contrast to variant modules, where one variant has always to be selected, optional modules can either be used or not when configuring a product variant [1].

However, individual requirements can often not be met exactly but only approximated by predefined and customer-anonymously designed variant modules [7–9]. Variant modules are developed for customer groups, not for the individual customer. In contrast to that, with product personalization (also called product individualization), customer individual requirements are met exactly using customer-specific product adaptations followed by a customer-specific product production [9–11]. In this paper, product personalization is understood to mean the adaptation of mechanical/physical components of a module of a physical product executed by the company in order to meet individual customer requirements.

In order to be able to apply product personalization in a complexity-controllable manner, the modular product architecture is supplemented by the variety type *personalizable* (see Fig. 1) [4,5,13,14]. A modular product architecture with decoupled, personalizable modules enables individual, customer-specific adaptation of the modules and included components without the adaptation propagating through the entire product architecture and influencing other modules or components [15]. Whether a module is personalizable, variant, or standardized is determined by the variety type of components contained in the module. The type of variety of the component with the greatest variety is transferred to the module.

In the context of personalization-oriented product design, areas of the product architecture are identified where customer-specific adaptations provide additional value for the customer and at the same time can be realized without or with only a low rise in complexity for the company [16]. Whereas product personalization promises greater value for the customer and thus represents a big chance for a company (competitive advantages, higher revenues through increased willingness to pay, etc.), it is also associated with a high level of personalization workload. Standardized

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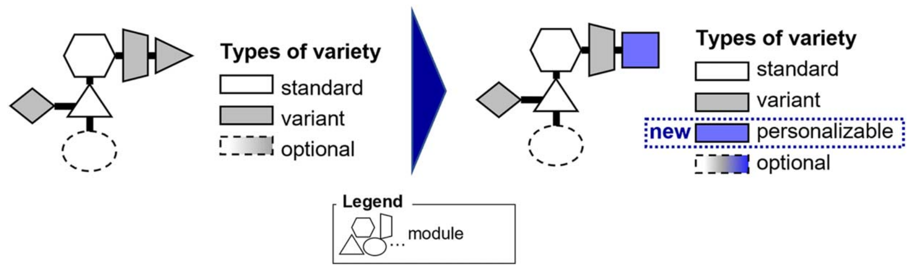

Fig. 1 Schematic representation of a product architecture of a product family, color coding of variety types according to Ref. [12]

individualization processes are necessary for order processing [17]. To make sure, that the initial cost of identifying and defining individualization potential in the product architecture and of redesigning and implementing standardized processes for realizing the customer-specific adaptations [18] are worth it, it is important to be able to define whether the advantages or disadvantages of a certain personalization project are greater in the long term. It must be possible for the company to easily capture and assess them in order to define a suitable product architecture. It is necessary that the effects of personalization become clear so that a company understands, which chances personalization offers and which are the pain points which need to be handled. Consequently, the following research question underlies this article:

How can a company be supported in deciding for or against more or less extensive personalizable modules in the product architecture? To answer this question, the effects of personalization for a product architecture should be systematically derived and summarized in an impact model. An impact model shows, according to Blessing and Chakrabarti [19], the desired future situation with its assumed impacts and effects. The aim of this paper is therefore to conceptualize an impact model of product personalization presenting possible positive and negative effects of product personalization on the different product life phases (Fig. 2). In addition, it shows how to apply the new impact model to an example.

Conceptual modeling describes "*the process of representing system-related knowledge*" [20]. Conceptualizing is a fundamental step for modeling mathematical and physical models in the future [20]. The gathering of effects, their presentation, and the overall mapping of personalization with modularization characteristics is the main contribution of this article. The models resemble a system dynamics model, where causal relationships are the focus [21].

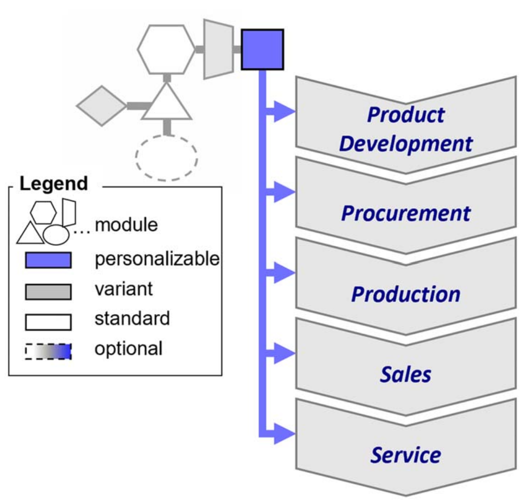

Fig. 2 Conceptualizing of an impact model to assess effects of product personalization on the different product life phases

In a generic model, the effects of the life phases should be listed as comprehensively as possible in order to be applicable to a wide variety of companies and products. Companies can then prioritize effects according to company- and product-specific circumstances in order to define strategies and identify cost-saving potentials. A company can use the model to investigate whether the consideration of personalizable modules can solve existing challenges or add new ones. Therefore, the final impact of economic targets needs to become clear. This work is therefore classified as basic research. A need for such a model has already been pointed out by Schwede et al. [22].

The following requirements (R) are placed on a model sufficiently answering the research question posed: A suitable model represents life-phase-specific effects (R1) of a modular product family (R2) considering product personalization (R3). Different effects should be linked with each other (R4), and the impact on the economic targets time, costs, quality, and flexibility should finally be displayed. Furthermore, a supportive visualization should be enclosed (R5).

In Sec. 2, the state of the art is introduced, and the research gap is underlined. The research method is presented in Sec. 3. In Sec. 4, the *Impact Model of Product Personalization considering Personalizability* (IMF + P), concentrating on the effects of *personalizability* in a modular product structure, is derived. Therefore, the new modularity characteristic of *personalizability* is developed, and a new index to quantify the degree of *personalizability* is introduced. For the holistic impact model, it is shown how effects and impact chains can be quantified and how to apply the developed model for a product example. A discussion of the results and the derivation of future research needs follows (Sec. 5), before the article ends with a conclusion in Sec. 6.

2 State of the Art

In this section, the fundamentals of modularization and personalization are explained. Existing literature is analyzed according to the effects of personalization, and it is deduced why existing approaches and models do not meet the requirements named in the introduction. In this way, the research gap is identified.

2.1. Design for Variety, Modularization, and Personalization. An increase in external variety demanded by the customer to better meet his requirements is accompanied by an increase in internal variety, which in turn leads to variant-induced complexity and affects all phases of a product's life (see Fig. 3(*a*)) [6,23,24]. According to Krause and Gebhardt [6], a life phase describes a company's function along the product creation or utilization. The generic life phases are product development, procurement, manufacturing, sales, and service/maintenance (see Fig. 2). They must be adapted and defined company-specifically. The external variety describes the variety of offered products, the internal variety, the variety of components, assemblies, part numbers, and processes within a company to provide the external variety [6,23]. The external and the internal variety are related to each other. Without suitable strategies, the internal

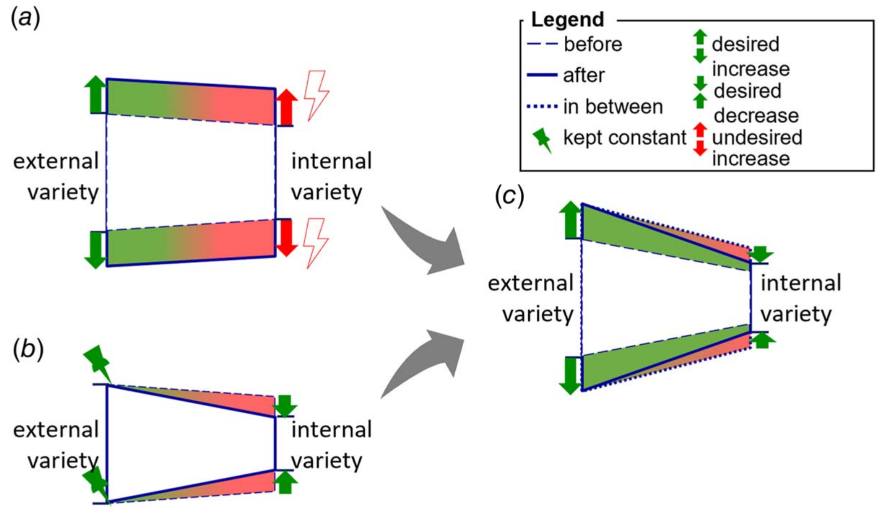

Fig. 3 Relationship between external and internal variety to highlight the difference between (*a*) uncontrolled variant generation, (*b*) variety-oriented product design and modularization, and (*c*) product personalization

variety increases as the external variety increases (see Fig. 3(*a*)). In product development, for example, an increase in external variety leads to many changes and new part numbers; in production, this leads to more complex work preparation and greater tooling times and costs; purchasing has to deal with more suppliers and requires greater storage capacities; sales has to manage and communicate a large number of very different product variants; in service, there are a large number of different spare parts and maintenance processes [6,23].

The costs arising from variety are referred to as complexity costs [25]. In contrast to manufacturing costs, these take into account not only material and production costs, but also the costs of all phases of life to deal with increasing variety [25]. By optimizing the product architecture and introducing modular and variety-oriented product architecture, internal variety and thus complexity costs can be reduced while keeping the external variety (see Fig. 3(*b*)). Initial investments are necessary to redesign the product architecture and its processes, but in the long term considerable costs, especially complexity costs, are saved [25,26].

To reduce internal variety, the given external variety is kept and the product architecture is designed, e.g., according to the ideals of *Design for Variety* [1,27]. Methods for a smart module definition are applied (e.g., according to Refs. [1,28,29]). In the sense of mass customization, modules with predefined standard or variant attributes can be produced economically in large quantities and configured with each other to form product variants, thus resolving the conflict between standardization preferred by the company and product differentiation demanded by the market. [30–32]. Depending on the aim and the modularization method used, different modular product architectures can be developed for a product family [22]. In order to describe the modularity of a product family architecture, the gradual modularity properties of *commonality* and *combinability*, which in turn are constituted by the modularity characteristics of interface standardization, oversizing, and function binding, can be used [33–35]. The modularity properties and the constituting characteristics are visualized in Fig. 4.

Commonality means that modules are used across different product variants of a product family. Commonly used standardized modules are used in all product variants of a product family, while commonly used variant modules are used in more than one but not in all. The higher the *commonality* of the modules of a product

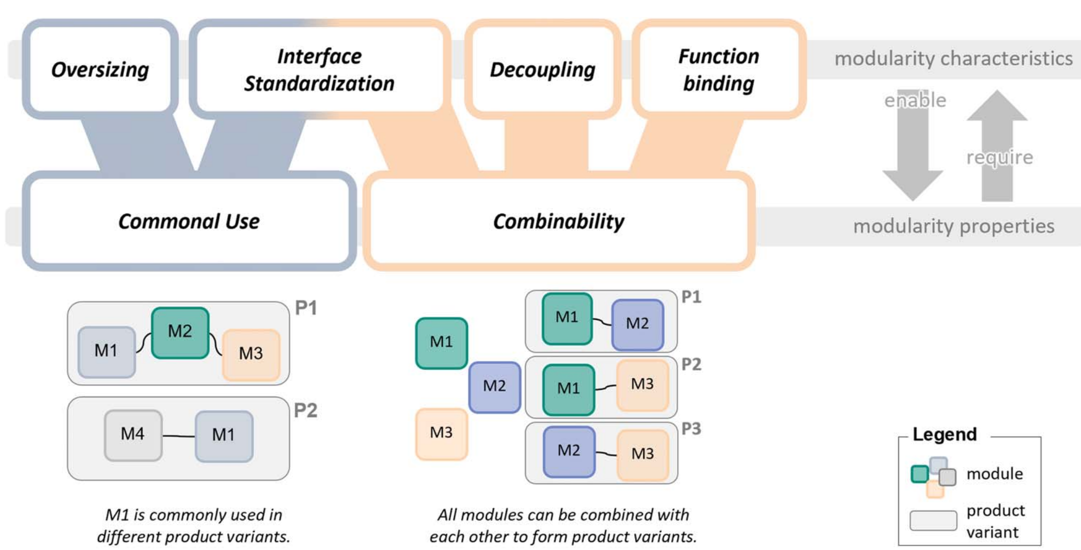

Fig. 4 Gradual modularity properties commonality and combinability and the constituting modularity characteristics (visualization based on Refs. [22] and [36])

architecture are, the smaller the number of modules needed for configuring the external variety [37]. *Combinability* describes the generation of different product variants by combining modules. Both, standardized and variant modules, are combined with each other. *Combinability* enables differentiation of the product range. The more combinable the modules of a product architecture are, the fewer product modules are required to generate a maximum number of different product variants [33]. For calculating *commonality* or *combinability*, the *Commonality* Index [37] and *Combinability* Index can be used [33]. Further modularity metrics are reviewed and discussed by Hölttä-Otto [38].

In contrast to commonly used methods for variety reductions and control, product personalization recently aims to achieve a controlled increase in external variety. At the same time internal variety hardly increases due to the prior planning and definition of a modular product architecture (see Fig. 3(*c*)). In the modular product architecture, personalizable modules with personalization scopes are preplanned and the customer-specific adaptation processes are defined. Negative effects on the company can be minimized by taking appropriate action. To do this, however, it is necessary to understand which effects are to be expected in the company in the individual life phases due to personalizable modules.

2.2. Impact Models of Different Product Architectures. Impact Models of Product Personalization, in which modular product architectures with personalizable modules are addressed, cannot be found in the literature. Ramesh et al. [39] name challenges of personalization for different life phases, but neither visualize the results nor present the chances of personalization.

However, there are impact models of modularity but they do not yet take product personalization into account. One of them is the *Impact model of modular product families* (IMF) by Hackl et al. [35], which was further developed by Schwede et al. [22] (see Fig. 5). In this model, effects and follow-up effects, which impact the life phases of a product within a company due to a modular product architecture, are presented in the form of impact chains. Effects are not only assigned to the modular structure per se, but more specifically to the properties of modularity and more precisely to *commonality* and *combinability*. The model of Hackl and Schwede is used to assess the impact of less or more *commonality* or *combinability* within a product architecture. It can also be used to clarify how *commonality* or *combinability* can be used to influence certain economic targets regarding time, cost, quality, and flexibility. Nevertheless, the model only implicitly considers personalizable areas in the product architecture.

Personalization is also not considered in other literature studies that examine the impacts of modularity. Hackl et al. [35] summarize some other models: Harland and Uddin [40] for example, summarize product platform effects and their interactions from the literature in a model; Boer [41] generalizes the impact of modularity on firm performance beyond the automotive and electronics industries. Other articles on the impacts of modularity focus more on the validation of effects found in the literature using studies (e.g., [42–44]).

2.3. Personalization Principles and Strategies. To offer a personalized product, different strategies can be applied. Some of them, like Mass Personalization [45], focus on the personalization of service aspects while keeping the physical product variants without individual adaptions. Others, like the product adaptability, concentrate on the upgradability of a product by the customer himself during product use [46]. This article focuses on product personalization strategies, where customer individual adaptions are realized by the company. This means a customer-specific definition of (certain) product characteristics, like a length or a diameter, for components of a personalizable module. The module is then manufactured for the individual customer. The configuration of modules, which are developed for market segments, as well as personalization through software solutions is not included in the scope of product personalization.

As described in the introduction is a modular product architecture the basis for personalizable products [11]. Flexible process structures are required in order to be able to make repeated customer-specific adaptations [5,47]. Different degrees of personalization exist [48,49]. One or more components of a module can be affected by personalization. Within a component, one or more characteristics can be personalizable [50]. It can be a simple scalability of the attributes of a characteristic, or an individual specification of shapes and forms of components that are difficult to express mathematically

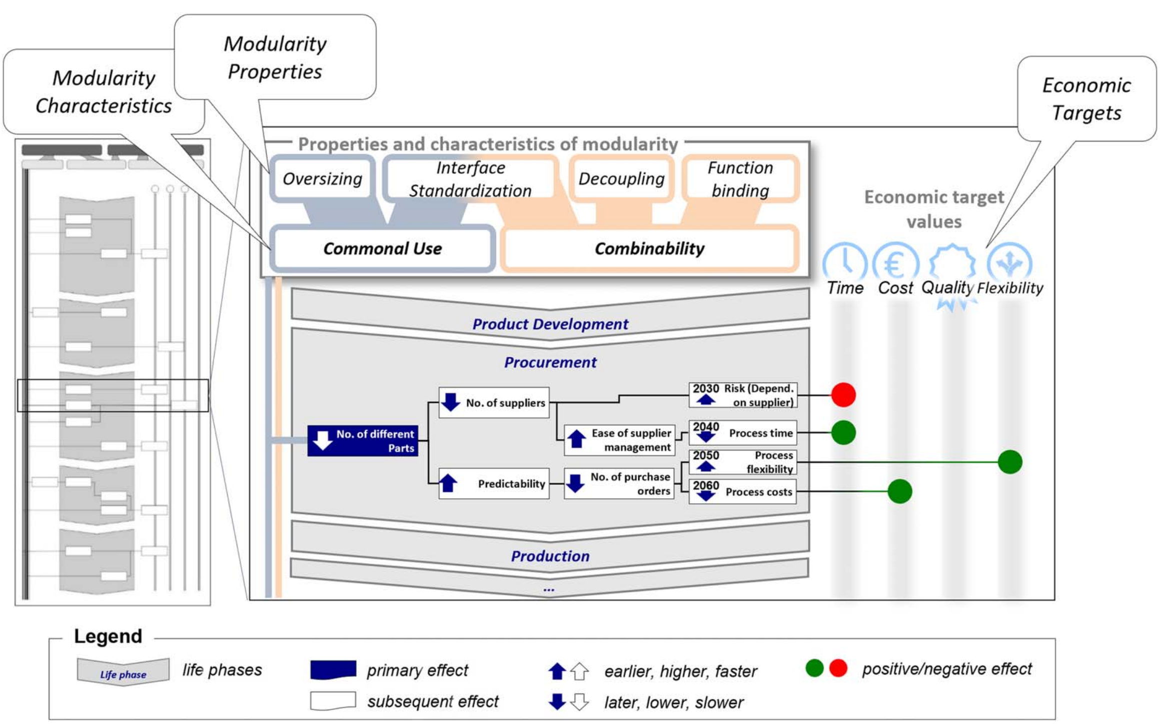

Fig. 5 Impact model of modular product families (IMF) according to Schwede et al. [22].

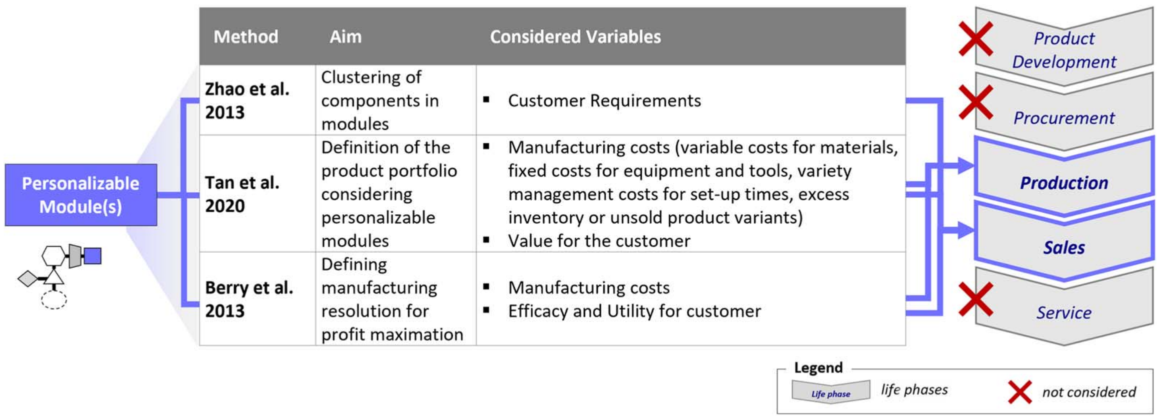

Fig. 6 Summary of existing approaches: Considered variables in the literature to evaluate personalizable modules in the product architecture and the associated life phases

(e.g., molding of anatomies for individual in-ear hearing aids or shoe insoles).

In order to design the product architecture of a product family and define the personalization degree, barely any method can be found in the literature. In *Design Adaptability*, according to Gu [46], existing designs are adapted to meet individual customer requirements, and customer-specific products are manufactured. However, no approach can be found that supports planning and implementing Design Adaptability in the product architecture. Koren et al. introduce the concept of *Mass Individualization*, where the customer is integrated into the design of the modules. The basis is an *Open Architecture* [32], which means a platform with standardized interfaces, where personalized modules can be attached to satisfy individual customer requirements [32]. A company no longer provides prepared modules for selection, but defines within the product architecture modules that can be designed according to a customer need [11,51]. There are only a few approaches to develop an open architecture; for example, Zhao et al. develop an open architecture using an extended quality function deployment (QFD) [52], Tan et al. present an algorithm for the optimal design of product architecture with standard, variant, and personalized modules [53], or Berry et al. determine the ideal number of attributes for a module algorithm-based regarding the perceived value and the manufacturing costs [13].

2.4. Conclusion From the State of the Art. The literature just generally names the conflict between customer satisfaction and cost increase [49], which needs to be considered when designing product architectures. But the causes of a cost increase remain untransparent and a holistic overview of what to analyze when evaluating personalizable modules in the product architecture for all life phases is missing.

The way of presenting the effects of product personalization according to Ramesh [39] fulfills the requirements, defined in the introduction to sufficiently answer the research question, R1 to R3 partly, R4 only rarely, and R5 not at all. The IMF of Hackl et al. and Schwede et al. meets the defined requirements R1, R2, R4, and R5 regarding an Impact Model for Product Personalization. Only R3, the integration of personalization, is missing. The other introduced impact models take product personalization only indirectly into account, if at all. Thus, R3 is not fulfilled by the models. Also, the assignment of the effects to characteristics of modularity (R2) is not given. Results are visualized rarely (R5). Therefore, the IMF is taken as the basis for the development of a new model.

For the product architecture design methods of Sec. 2.3, it is possible to read out indirectly from the optimization variables in which company effects are considered when evaluating product personalization in the product architecture. Figure 6 summarizes the presented methods and the analyzed variables. It becomes clear, that all of them focus on the customer view and thus the effects for the sales life phase and the impact for the production life phase. The impact on all other life phases is neglected.

The aim of this paper is therefore to conceptualize an Impact Model of Product Personalization that depicts the effects in all life phases due to personalizable modules in a product architecture. With the help of such a model, the effects of product personalization in a modular product family can be assessed, the implementation of product personalization can be evaluated holistically, and processes can be organized and planned in a targeted manner. The next section explains the associated research method for conceptualizing an Impact Model of Product Personalization, before the final model is presented.

3 Research Method

The conceptualization of the new impact model considering product personalization started with a literature search. A search in the Scopus database for the keyword *personali** in combination with *product* and *impact*, *effect,* or *consequence* in the area of *engineering* and in English language resulted in 38 hits, but none of them can be classified as relevant because they do not deal with the personalization of physical products by a company or do not focus on the effects or impacts of personalization. Replacing the word personali* with the term individuali* also yields no hits in which the impacts of product personalization are explained.

After the first literature research could not reveal a satisfactory model, it is necessary to conceptualize a new model. Figure 7 summarizes the research procedure. The IMF according to Hackl and Schwede is used as a basis for the new impact model. The IMF offers, in contrast to the other models from the literature, the large advantage that affects the different modularity properties can be attributed to cause-appropriate. Since so far *commonality* and *combinability* are focused as causes, it is analyzed, by which modularity properties the consideration of personalizable modules in the product architecture can be described. For this purpose, the definitions and visualizations of the known modularity properties are examined in detail and extended (Fig. 7, Step 1).

In the following, with the help of a literature review, the effects and impacts of a modular product architecture with product personalization are collected from individual literature studies (Fig. 7, Step 2). For this purpose, the terms *(product) personalization*, *(product) individualization*, *personalized product,* and *individualized product* are searched for in both, English and German language, in the Scopus database, Google Scholar, the Design Society site, and the homepage of University Libary of Hamburg Technical University.[2] The literature is scanned for effects. Effects found are compared with the effects from the IMF and either noted as new effects or

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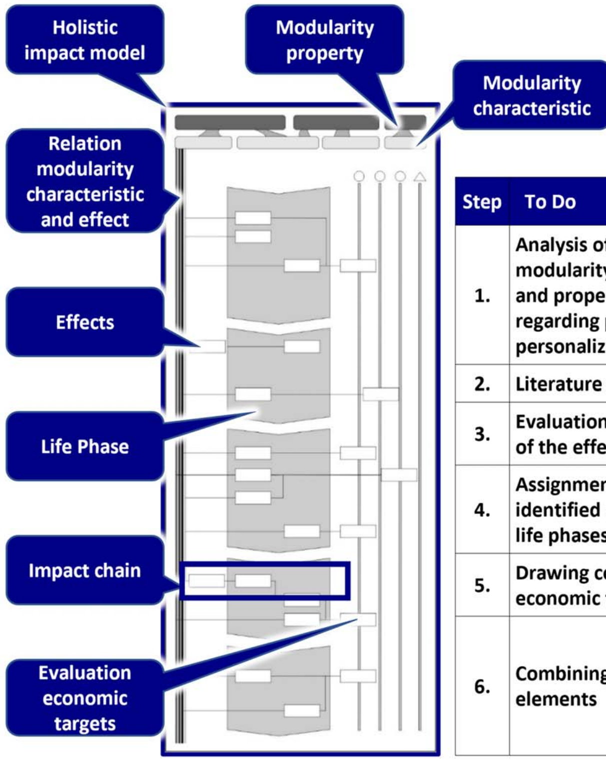


Step	To Do	Output
1.	Analysis of known modularity characteristics and properties of IMF regarding product personalization	New modularity characteristic, constituting modularity properties
2.	Literature review	Effects
3.	Evaluation and extension of the effects of the IMF	Life-phase specific effects and impact chains
4.	Assignment of the identified effects to the life phases	
5.	Drawing conclusion for economic targets	Evaluation economic target
6.	Combining the different elements	Holistic impact model for modular product families including personalizable modules

Fig. 7 Description of the holistic impact model and research method on how to assess the different elements

depicted with the known wording from the IMF but with the new evaluation concerning *personalizability* (Fig. 7, Step 3), with the latter being favored. The effects are all assigned to the life phases of product development, procurement, production, sales, and service/maintenance (Fig. 7, Step 4). The implicit knowledge helped to derive which of the economic targets time, cost, quality, and flexibility an effect has an impact on and whether there is a positive or negative coupling (Fig. 7, No. 5). After deriving the effects and impact chains of *personalizability*, the results are combined with the effects of common use and *combinability* of IMF to get a holistic impact model for modular product families considering personalizable modules (Fig. 7, No. 6). The research method for deriving the impact model is once again depicted in Fig. 7.

4 Impact Model of Product Personalization

This section presents the results obtained when using the research method described in Sec. 3.

4.1. Relation of Personalization and Modularity. As described in Sec. 2.1, commonly used modules are used in all product variants of a product family, while commonly used variant modules are used in more than one but not in all. On the other hand, *combinability* describes the generation of different product variants by combining modules and thus enables differentiation of the product range. By deciding on a level of *commonality* and *combinability,* a modular product structure could be determined in the modularity space. While deciding on a level of *commonality* or *combinability*, the IMF can be used to evaluate the effects of higher or lower *commonality* and *combinability* in the product architecture. Now, the modularity space is extended since personalizable modules need to be considered while designing the product architecture (see Fig. 8). To describe this, the new modularity characteristic of ***personalizability*** is defined.

A new modularity property describing the characteristic of *personalizability* is the *adaptation scope*, which describes what can be adapted in the modular product architecture and within what limits. This has to be defined while product architecting. Furthermore, the known properties of *interface standardization* as well as *decoupling* are also valid for *personalizability*. The more decoupled the modules are, the less *personalization propagation* takes place and the less characteristics of other modules are affected by the personalization of a characteristic. Interface standardization favors personalization.

The more modules or the more characteristics of the modules of a product architecture are personalizable, the higher the *degree of personalizability*. The higher the *decoupling* of modules of an architecture are, the higher the *degree of personalizability*. Figure 9 quantifies this relation in a new developed index, the *personalizability degree* (PD). A higher or lower degree of *personalizability* in a product architecture can be achieved by changing the *adaptation scope* or the *decoupling*. In product architecture A, for example, two characteristics of module 1 are personalized ($AS_{M1} = 2$). The product architecture consists of three modules ($n = 3$). The module is not coupled with other modules ($c_{M1} = 0$). Following the formula, the PD results in $\frac{\frac{2}{1+0}+\frac{0}{1+0}+\frac{0}{1+0}}{3} = 0{,}67$. If now not only two but four characteristics can be personalized ($AS_{M1} = 4$), the PD increases since $\frac{\frac{4}{1+0}+\frac{0}{1+0}+\frac{0}{1+0}}{3} = 1{,}33$. On the other side, if two characteristics of one module are personalized but are coupled with a coupling factor of 1 with one other module ($c_{M1} = 1$), the PD decreases since $\frac{\frac{2}{1+1}+\frac{0}{1+0}+\frac{0}{1+0}}{3} = 0{,}33$. The more coupled the module with personalizable characteristics is, the lower the personalizability degree. Determining a suitable degree of *personalizability* in the product architecture is a central issue of personalization-oriented product design.

In the following, the original IMF, which focused so far on *commonality* and *combinability*, is extended and the new modularity property of *personalizability* is included as a cause. Its effects on the different life phases are analyzed and visualized.

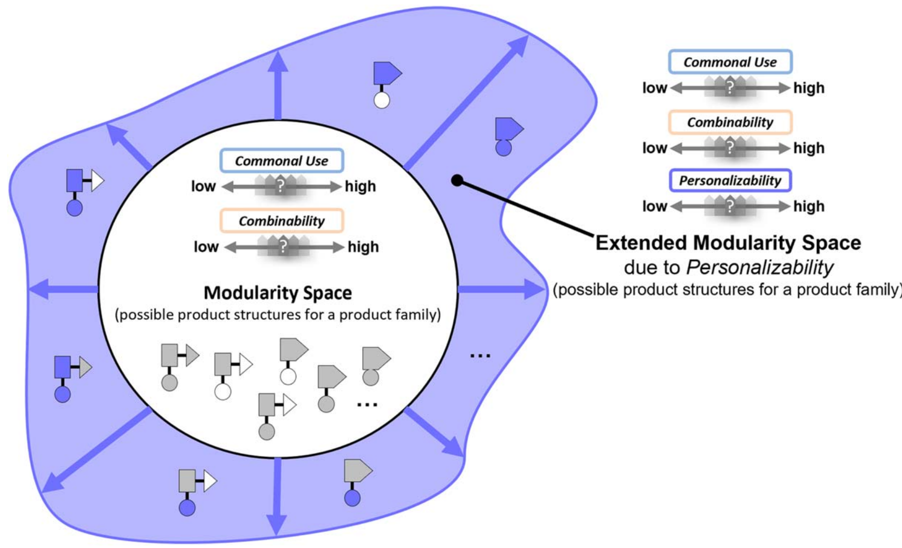
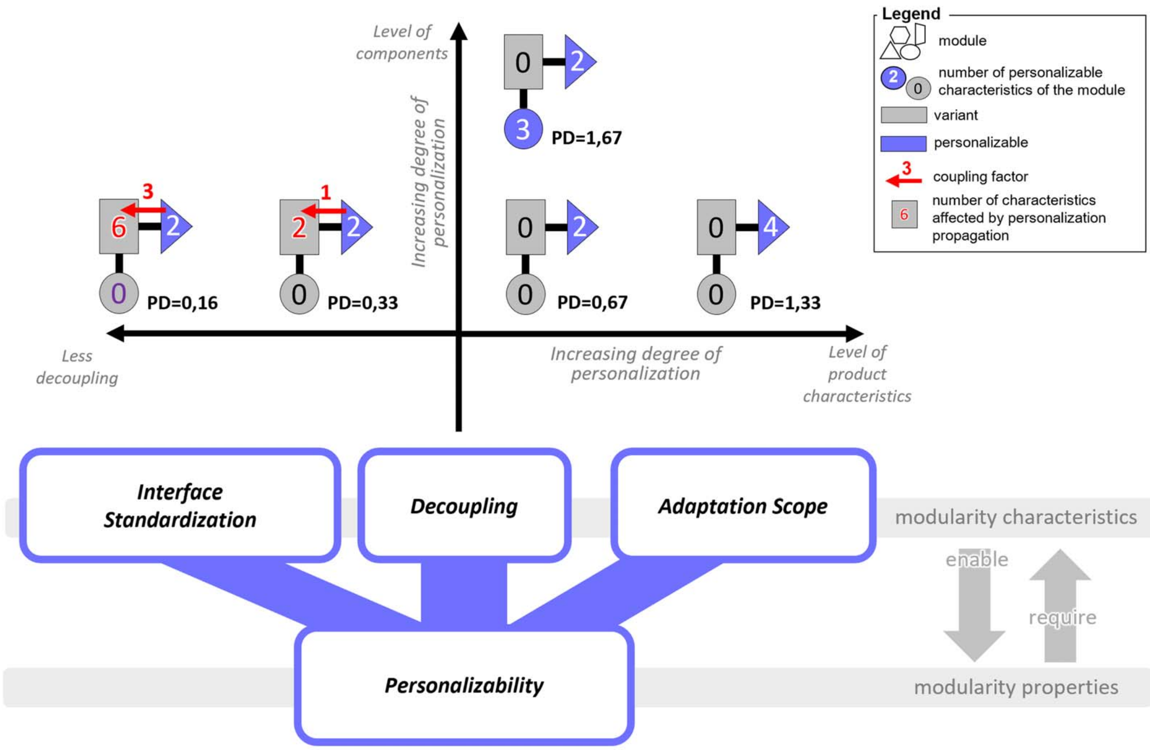


Fig. 8 Extension of the modularity space due to the consideration of personalizable modules in the product structure



$$\textbf{Personalizability Degree (PD)} = \frac{\frac{AS_{M1}}{1+c_{M1}} + \frac{AS_{M2}}{1+c_{M2}} + \frac{AS_{M3}}{1+c_{M3}} + \cdots + \frac{AS_{Mn}}{1+c_{Mn}}}{n}$$

AS number of personalizable characteristics
c coupling factor (dependent characteristics of other modules)
M module
n total number of modules in the product architecture

Fig. 9 The new modularity characteristic personalizability and the constituent modularity properties including an explanation for the degree of personalization in a product architecture to define the adaptation scope

4.2. Effects of Personalizability. The modularity of different product architectures can now be described by the characteristics of *commonality*, *combinability,* and *personalizability,* which can be used independently from each other. While *personalization* generally describes the targeted reaction to individual customer needs (e.g., by personalized services or personalized products), ***personalizability* describes the capability of a modular product family to realize product personalization**. Including a suitable degree of *personalizability* in the modular product architecture makes it possible to personalize the product in a way that is manageable in terms of complexity.

In the literature, the effects and impacts of product personalization are, if at all, mostly mentioned in general terms, but not questioned further or related to a modular product architecture. This is the major unique value of this article. Impacts and effects of product personalization are collected from the literature (see collection of quotes in the Appendix).

Impacts and effects, that are no longer expected to occur with the implementation of a modular product architecture, are not considered. As in the IMF, only the effects of implemented modular structures are shown; the initial effort for redesigning the processes adapted to a stronger or weaker communal, combinable, or personalizable product architecture is not depicted. This relates to the definition of an impact model describing the future situation and not the way to achieve it [19].

Figure 10 shows some examples of how to use the collected quotes to get the effects in the life phases. First, the addressed life phases of a quote are determined. Then, primary and secondary effects of the original IMF are identified to which the quote fits. It is determined whether a higher *personalizability degree* is expected to improve or worsen the effect. New effects, which were not in the IMF, are added.

For example, Ramesh et al. [39], Aheleroff et al. [49], Hu [5], Berry et al. [13], Piller et al. [56], or Wang et al. [54] mention the higher degree of customer co-creation due to a more intensive product personalization. This cannot be expressed by the existing effects in product development of IMF; therefore, the new effect *Co-Design* is added. The higher the degree of *personalizability* in a modular product structure, the more pronounced the effect is and the more intensive is the cooperation with the customer during product definition. This yields a higher product quality but also an increase in design workload for the product development life phase. This in turn results in longer process times, so that the economic target time is negatively affected in total.

Another example is the reduced predictability for procurement and production scheduling [39]. The IMF includes *Predictability* as an effect for procurement so that it can be evaluated here, but for production, the effect is added.

The existing effect *Staff Training* in Production, Sales and Service is addressed by Uhlmann et al. [59]. This means, that when increasing *personalizability* in the modular product architecture, the need for an increase in staff training is needed. This means higher training costs for the company and thus higher process costs. The economic target cost is affected negatively.

One last example affects the sales life phase. Statements of Ben-Jebara and Modi [58] or Reichwald et al. [18] evaluate the turnover with product personalization and thus can be related to an existing effect of IMF. Statements of Günthner et al. [57] and Wang et al. [54] address the increase in "*material flow and control effort*"

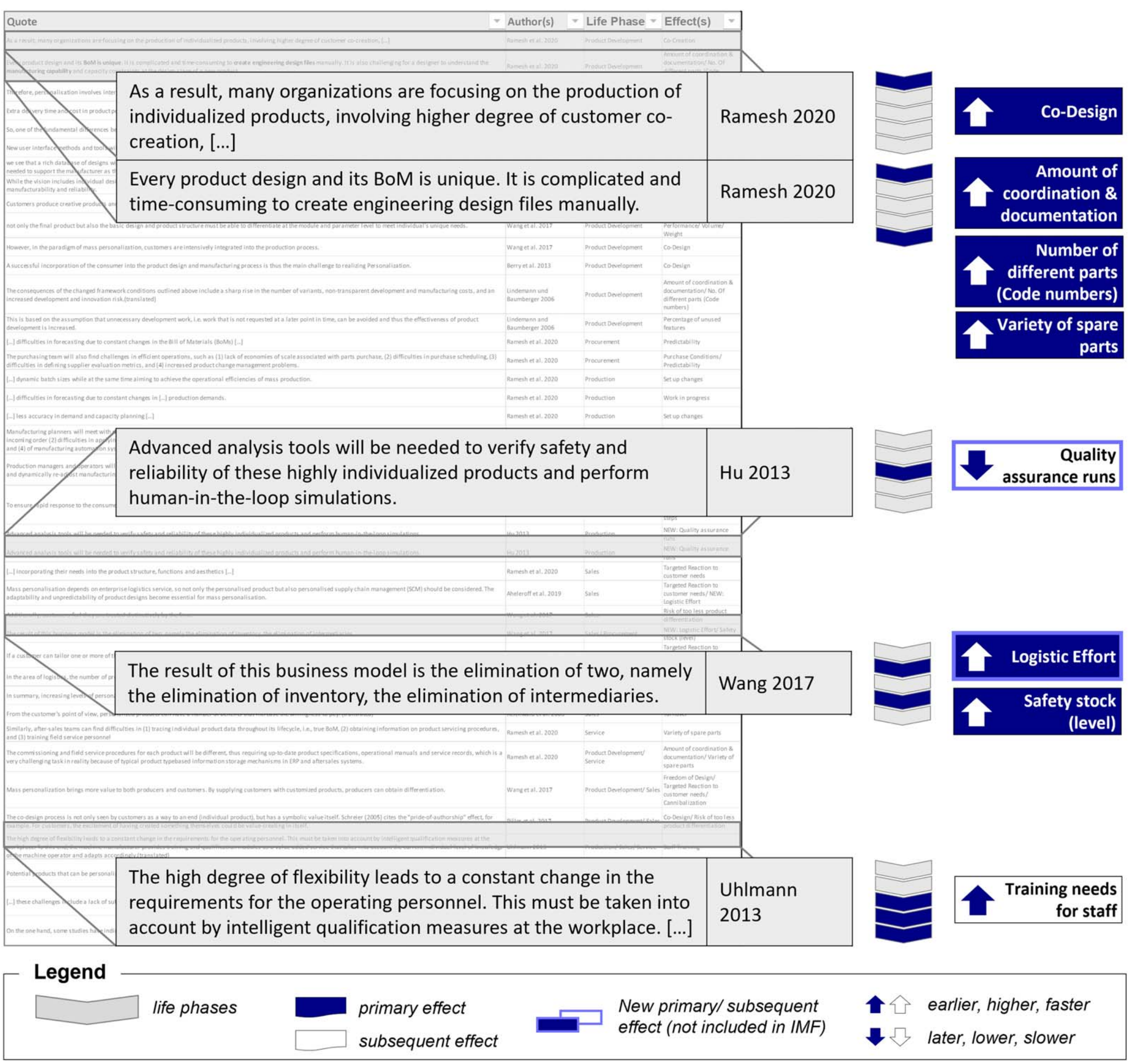


Fig. 10 Using statements from the literature to draw conclusions about the effects of personalizability

and the "*elimination of intermediaries."* These statements are summarized in the new effect of logistic effort.

In this way, all quotes are examined, assigned to life phases, and effects with directions of impact are identified.

Furthermore, some general effects, which cannot be assigned to one life phase, are identified. This includes the reduction of the *lot size*. Modules are no longer designed for customer groups, but for individual customers, which means that the lot size is equal to one for the personalizable module. Personalized components and parts have to be realized and managed within a standardized order processing in the company [17]. A more intensive networking of the divisions of a company is necessary to communicate individual requirements and the resulting product adaptions [60]. According to Lindemann et al. [60], close collaboration with the customer throughout all product life phases requires the introduction of suitable communication tools and channels. An intensive data management is required. Aheleroff [49] states that for real-time information during personalization process, deep learning and machine learning technologies can be applied. It is important to be able to trace individual product data throughout the whole lifecycle to make sure, that the customer gets the product that is specified for him. Therefore, Ramesh [39] suggests the use of digital twins. The digital twins of the different life phases "*create a seamless Digital Thread, capturing the lifecycle information of each personalized product*" [39]. Lindemann et al. [60] state, that product personalization means that the product is less likely to be discarded. The customer can identify more strongly with the product, which can increase the usage time and thus the lifetime of the product [60]. More detailed investigations should be carried out to determine the relationship between product personalization and certain aspects of sustainability.

In order to control variety-induced complexity, the literature often mentions that flexibility is a prerequisite for personalization, especially manufacturing flexibility [13,32,47,53]. However, this flexibility should not be mixed with the economic target flexibility that can be created by personalization. While manufacturing flexibility is needed to implement *personalizability* on a mass scale, the impact on the economic targets only becomes clear through the analysis of the effects after having implemented *personalizability* in the product architecture. The economic target of flexibility mainly refers to product or portfolio flexibility, which is given by an implemented product architecture. For example, through *personalizability* in the product architecture, the design of the components is not completely fixed, which creates product flexibility.

4.3. Consolidation to a Holistic Impact Model of Modular Product Families (IMF + P). The effects found depending on the degree of *personalizability* are combined with the effects of *commonality* and *combinability* included in the IMF to create a *Holistic impact model of modular product families* (IMF + P). The effects and impacts of each life phase are presented. The primary effects already known from IMF are filled in dark blue and subsequent effects in white. As before for IMF, an arrow pointing upward indicates an increase, while the arrow pointing downwards indicates a decrease for the specific effect of the IMF + P. However, the direction of impact has to be specified depending on the company's constraints. It is derived on which economic target the effects have an impact. A green circle on the right symbolizes that there is a positive effect on the economic target, while a red circle illustrates a negative impact. It must be noted, however, that the directions are only general assessments, and company and product-specific conditions can affect them.

Figure 11 shows a cutout of the IMF + P. The whole IMF + P can be found in Appendix.

The extended impact model no longer focuses only on standardized and variant modules in the modular product architecture, but also takes personalizable modules into account. The effects of a modular product architecture with a larger or smaller *personalizability degree* can now be traced back to the new modularity property. **The higher the *personalizability degree*, the more pronounced the positive and negative effects in the different life phases. Is the *personalizability* smaller due to a coupling between modules, the negative effects are intensified.**

The existing mathematical formulas of the key performance indicator (KPI) developed by Greve et al. [61] for the IMF can also be used to quantify the effects in the IMF + P, since the effects are mostly the same. For example, the impact of the worsened *purchasing conditions* can be quantified by multiplying the lot size by the costs per unit [61]. The increase in *training for staff* can be quantified by multiplying the time per training process by the number of repetitions [61]. Together with the cost rate per hour, costs can be determined. Figure 12 visualizes for some effects and impact chains how quantification of the economic targets can be achieved. However, our experience in the application of the impact model clearly shows that most companies have their own KPIs to evaluate effects. At this point, it should be emphasized once more that company and product constraints can mean that not all of the effects listed play a role or that some effects can be neglected in a company.

4.4. Application of the IMF + P. The impact model extended by *personalizability* IMF + P can be used by companies to decide on the orientation of a modular product architecture. With the help of the IMF + P, companies have an overview of all possible effects and can

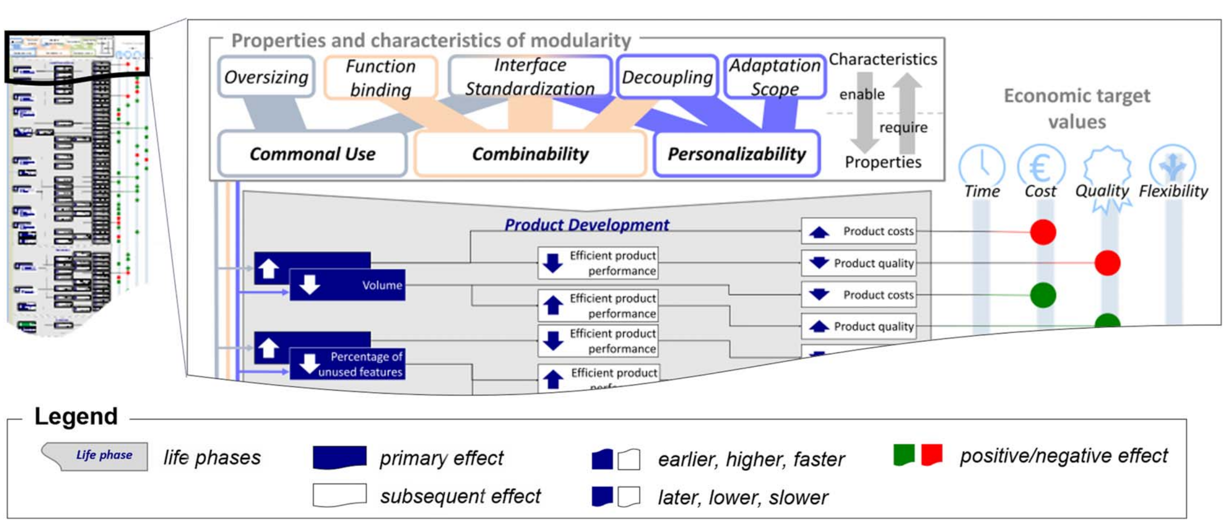


Fig. 11 Consolidation of the findings with to a holistic impact model of modular product families (IMF + P)

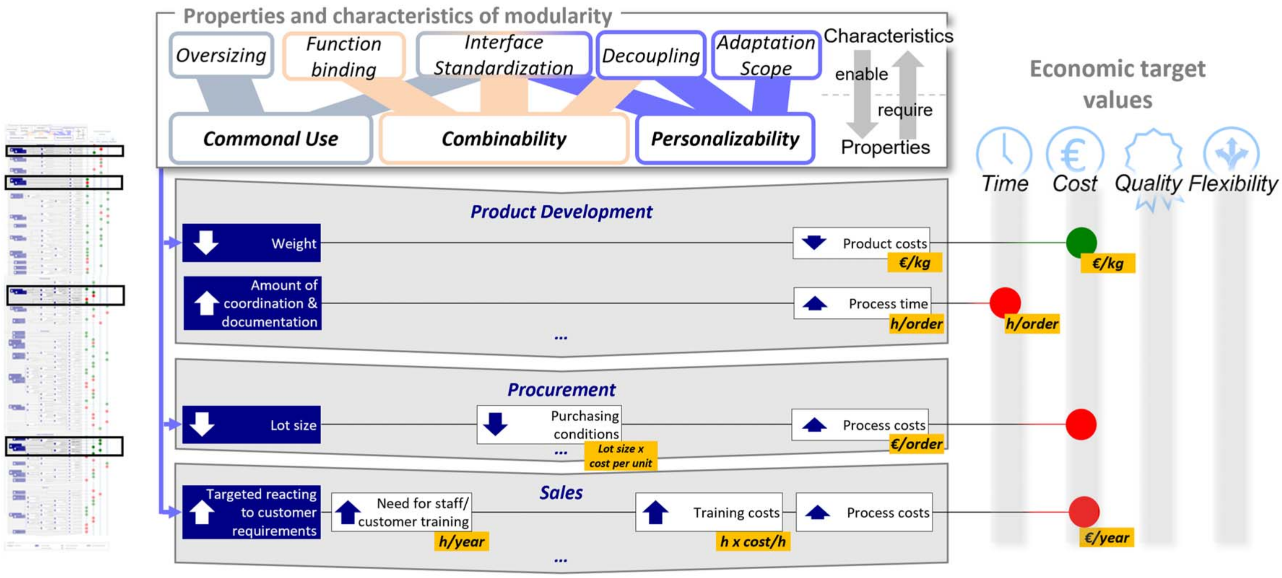


Fig. 12 Examples of impact chains with generic quantification based on the KPIs according to Greve et al.

pick out the effects that are most important to them and examine them in more detail. For this purpose, representatives of the different life phases can come together and prioritize effects and impact chains in a workshop, i.e., which effects in particular should be achieved by the modular architecture. If, for example, volume or weight is a critical aspect that often prevents customers from buying the product, or that could make the customer very satisfied if it were fulfilled more precisely, this effect can be found in the IMF + P. It becomes clear that greater *commonality* in the product architecture leads to an increase in volume, while personalization can lower volume. On the other hand, *personalizability* can, e.g., lead to tooling costs increasing. These can be reduced by *commonality*.

An exemplary application situation could be that a company is faced with the decision to integrate personalization into the product architecture or not. Personalization is one of the current megatrends that companies are trying to follow and are not quite sure how this trend can affect their own products. With the help of the IMF + P, it can be examined whether the negative effects of *personalizability* would lead to an excessive burden that would not outweigh the positive effects. The following steps need to be carried out:

(1) Development of alternative product architectures with personalizable modules.
(2) Prioritizing the effects and impact chains in the IMF + P.
(3) Determination of quantifiable values for the prioritized impact chains (if necessary, orientation to the KPI developed by Greve et al. [61]).
(4) Calculation of the values and decision-making process.

This decision was also made by a company involved in the development of a flow diverter, a medical stent for the treatment of pathological cerebral vascular stenosis [10]. The company aimed to improve product performance to reduce complications with the stent during treatment and stent implantation. There has been discussion about personalizing the diameter or length of the stent to match individual patient pathology [10]. The personalization degree of the modular architecture with the personalized diameter is lower than for a personalized length, since the diameter is not completely decoupled from another module (Fig. 13, No. 1).

The most important effects for the company to be evaluated are *Efficient product performance, Tool/Jig investment, Need for staff/customer training,* and *Communication Effort* (Fig. 13, No. 2). For the effects, company-specific quantifications are developed (Fig. 13, No. 3). For evaluating the product performance, the distance between the blood vessel wall and the implant is measured; for evaluating the tool investment, the tool cost per piece is analyzed; the staff training is quantified in hours per year and the communication effort is quantified by the hours required for implant specification with the physician.

In product development, it has been proven that a personalized diameter has a positive impact on product performance due to better wall apposition of the stent. However, the negative effect of the production life phase describing the increase of the tooling costs was estimated to be so high (tool price per piece instead of per lot, 20 times higher cost) that this effect outweighed the increase of the willingness to pay for the lower complication rate (Fig. 13, No. 4). In the case of the flow diverter, no personalization of the diameter was enforced due to the strong negative effects of production. On the other hand, no new tooling is needed for a personalized length. Although the communication effort increases due to more intensive clarification of exact patients' requirements, the positive effect of the more efficient product performance outweighs the negative effect here. The time for staff training and thus the costs stay the same, since the training to manipulate the implant to fit the individual vessel is as high as the training for implanting a personalized device.

The IMF + P can help to systematically record and evaluate the positive and negative effects of personalization on a company. The weighting of the effects must be done company- and product-specific.

5 Discussion of the Findings and Outlook

The IMF according to Hackl and Schwede has proven to be a suitable basis for the IMF + P. Many of the effects listed there could also be evaluated to personalization, as confirmed by the literature. The IMF on which the IMF + P is based has been validated in a variety of ways [22,61–63]. In industry-related research projects, the IMF is used to clarify the direction of the modularization project at the outset [64]. The IMF + P, including personalization, can be a great added value in these situations. At the same time, the industry-related workshops can be used for large-scale validation.

Comparing the results of the new modularity characteristic of *personalizability* with the effects of the original model shows that many of the effects of *commonality* are reversed. This is not surprising, because, while *commonality* tries to use the same module as widely as possible through oversizing and standardization, *personalizability* aims to use a module really only for a single customer.

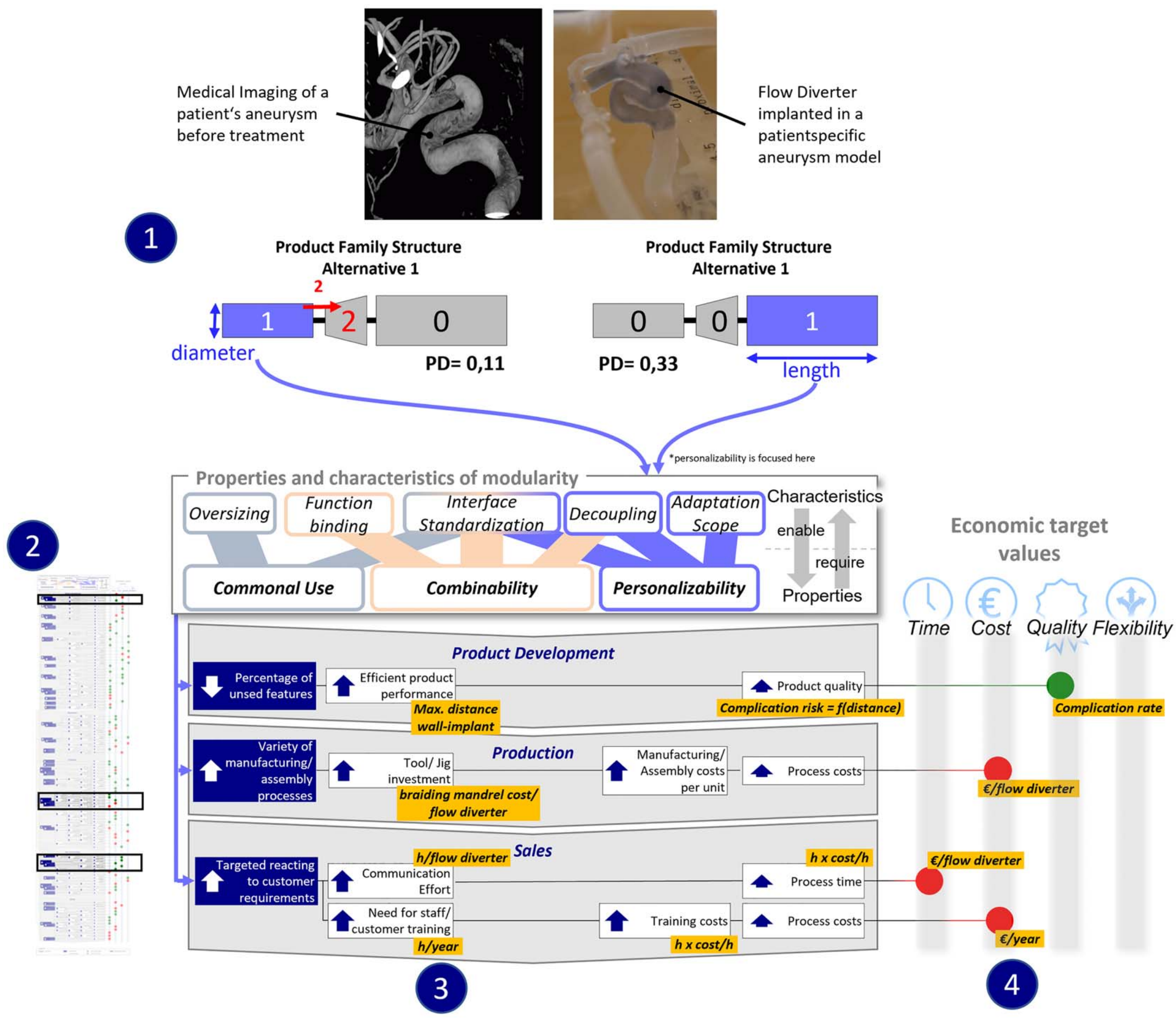


Fig. 13 Application of the IMF + P for evaluating different product architectures of the flow diverter quantifying the prioritized effects and impact chains

Personalizability often has opposite effects than *commonality*. However, the more decoupled a personalized characteristic and the more standardized the process of realizing personalized modules are, the less impact the negative effects get and the higher the impact of the positive effects are.

The effects of *combinability*, on the other hand, remain largely unchanged and do not play any role in *personalizability*. This can be explained by the fact that *combinability* and *personalizability* both pursue the goal of differentiation. *Combinability* concentrates on how to achieve differentiation; personalization focuses on how much differentiation is appropriate.

Commonality, *combinability,* and *personalizability* are independent descriptors to compare the modularity of different product architectures. *Personalizability* in general seems to influence the economic target of *quality* in particular. As can be seen, e.g., for production, many effects have a negative impact on the economic targets, especially on time and costs. Here, and also in all other life phases, standardized but flexible product and process structures as well as experienced employees may help to control those negative effects and not give them so much weight in total.

It can also be observed that, in general, smaller lot sizes and lower economies of scale occur and increase costs. Here, suitable measures to reduce costs must be examined or the customer's willingness to pay for a personalized product must increase accordingly. Methods for price calculation and targeted costing from controlling can be used here. Also, the negative cost and time effects that can arise from customer-specific adaptations can be greatly reduced through the targeted planning of personalization scope and the associated execution processes. The implementation of a standardized individualization process [17] is essential.

When researching the effects and impacts of modular product architecture with a personalizable component, it was hard to find literature focusing on effects and impacts, and it was mostly only a side issue. The search for the effects of personalization (without explicitly highlighting a modular product architecture) yielded only some results. Even in the book of Lindemann et al. [55], summarizing the results in the area of personalization of a Collaborative Research Centre (German Research Foundation) of different German institutes, the effects of personalization in a modular product architecture are not summarized or visualized. Nevertheless, some effects could be located in the literature and the IMF + P could be derived from the implicit knowledge acquired. The search can be extended to include other keywords the authors are not aware of at this point.

The research question posed at the beginning could be answered with the results of this article. Through the IMF + P, a company can be supported in deciding for or against more or less extensive personalizable modules in the product architecture. The conceptualized model provides a basis for deriving mathematical and physical models in future work.

Further future work could study the long-term effects of modular structures with personalization, similar to Greve and Krause [65]. Furthermore, as soon as more methods for designing modular product architectures with personalization are published, these methods can be linked to the effects of *personalizability* in the IMF + P, analogously to Ref. [22].

As more and more data on the IMF were collected in extensive research, a model-based implementation of the IMF using the SysML modeling language was chosen. In this model, not only the two-dimensional relationships are stored which the IMF shows, but also linked data such as company boundary conditions, KPIs, or probabilities of occurrence of individual effect chains [22,66]. The advantage of the modeling is that the data and data relationships can be stored centrally in one place and key figures can be assigned to the effect chains [61]. An Excel interface enables communication with the model. The data can be filtered in the Excel sheet. For example, effect chains can be prioritized based on given company boundary conditions. If additional empirical data is collected on the effect chains, it can also be integrated into the SysML data model via the Excel interface. However, since the data model/SysML model is not a big novelty [61,66], little focus has been put here by the authors of this article. Nevertheless, the aim of further research is to integrate the new findings presented in this paper into the data model in order to strengthen it.

6 Conclusion

In this paper, a *Holistic impact model of modular product families* (IMF + P) is derived. For this purpose, a literature study is conducted. Effects and impacts from the *Impact model of modular product families* (IMF), which has so far been limited to *commonality* and *combinability*, are analyzed and extended by the effects of *personalizability*. The results are visualized based on the IMF according to Hackl and Schwede. For the new modularity property, a new index is developed to quantify the personalization degree of a product architecture.

The developed IMF + P is intended to support companies in assessing the effects and opportunities of taking personalization into account in modular product architecture design. Thus, this work contributes significantly to being able to consider personalization in the development of modular product architectures by default and to be able to estimate positive and negative effects and impacts.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

Nomenclature

c = coupling factor (dependent characteristics of other modules)
n = total number of modules in the product architecture
M = module
AS = number of personalizable characteristics
IMF = impact model of modular product families
$IMPF + P$ = holistic impact model of modular product families
PD = personalizability degree

Appendix

Table 1. Literature quotes and the derivation of effects of personalizability for the different life phases

Quote	Author(s)	Life phase(s)	Effect(s)
As a result, many organizations are focusing on the production of individualized products, involving higher degree of customer co-creation, […]	[39]	Product development	Co-creation
Every product design and its **BoM is unique**. It is complicated and time-consuming to **create engineering design files** manually. It is also challenging for a designer to understand the **manufacturing capability** and capacity constraints at the design stage of a new product	[39]	Product development	Amount of coordination and documentation/No. of different parts (code numbers)
Therefore, personalisation involves internal (what a person needs) and external (environmental) data collection	[49]	Product Development	Co-creation
Extra delivery time and cost in product personalisation is highly dependent on the individual's interaction with things consist of products, services and people.	[49]	Product development	Co-creation
So, one of the fundamental differences between personalisation and mass personalisation is customer engagement in the UX and co-design process	[49]	Product development	Co-creation
New user interface methods and tools will be needed to support the scalable user experience and collaborative, distributed design approaches	[5]	Product development	Co-design
we see that a rich database of designs will be constantly evolving for the manufacturer to use in identifying potential new markets and new products. Tools and algorithms will be needed to support the manufacturer as the company seeks to data-mine the design space to identify trends and emergent designs which signal new markets and new product potential	[5]	Product development	Innovation
While the vision includes individual designers having the freedom to fully personalize a design, the reality is that the design space is bounded, often by limits on safety, manufacturability and reliability	[5]	Product Development	Freedom of Design
Customers produce creative products and gain value through cooperating with manufacturers	[54]	Product development	Innovation
not only the final product but also the basic design and product structure must be able to differentiate at the module and parameter level to meet individual's unique needs	[54]	Product development	Efficient Product Performance/Volume/Weight
However, in the paradigm of mass personalization, customers are intensively integrated into the production process	[54]	Product development	Co-Design

Table 1. ***Continued***

Quote	Author(s)	Life phase(s)	Effect(s)
A successful incorporation of the consumer into the product design and manufacturing process is thus the main challenge to realizing Personalization	[13]	Product development	Co-Design
The consequences of the changed framework conditions outlined above include a sharp rise in the number of variants, non-transparent development and manufacturing costs, and an increased development and innovation risk.(translated)	[55]	Product development	Amount of coordination & documentation/No. Of different parts (Code numbers)
This is based on the assumption that unnecessary development work, i.e., work that is not requested at a later point in time, can be avoided and thus the effectiveness of product development is increased	[55]	Product development	Percentage of unused features
[…] difficulties in forecasting due to constant changes in the Bill of Materials (BoMs) […]	[39]	Procurement	Predictability
The purchasing team will also find challenges in efficient operations, such as (1) lack of economies of scale associated with parts purchase, (2) difficulties in purchase scheduling, (3) difficulties in defining supplier evaluation metrics, and (4) increased product change management problems	[39]	Procurement	Purchase Conditions/Predictability
[…] dynamic batch sizes while at the same time aiming to achieve the operational efficiencies of mass production	[39]	Production	Set up changes
[…] difficulties in forecasting due to constant changes in […] production demands	[39]	Production	Work in progress
[…] less accuracy in demand and capacity planning […]	[39]	Production	Set up changes
Manufacturing planners will meet with difficulties in production planning and scheduling as a result of (1) a lack of timely knowledge of the design and quality requirements of the incoming order (2) difficulties in applying common production control strategies, such as determining batch sizes, Kanban and CONWIP (3) constant changes to BoM between orders, and (4) of manufacturing automation systems, such as ERP and MRP systems	[39]	Production	Set up changes/Work in progress
Production managers and operators will need to (1) execute distinct manufacturing routes for different orders, (2) tracking production progress and quality by every individual order, (3) and dynamically re-adjust manufacturing operations based on real-time production progress and new incoming production orders	[39]	Production	Variety of manufacturing/assembly processes
To ensure rapid response to the consumer demand, the manufacturing system must provide flexibility in fabricating personalized product features and modules	[5]	Production	Set up changes/No. of unnecessary manufacturing/assembly steps
Advanced analysis tools will be needed to verify safety and reliability of these highly individualized products and perform human-in-the-loop simulations	[5]	Production	NEW: Quality assurance runs
Advanced analysis tools will be needed to verify safety and reliability of these highly individualized products and perform human-in-the-loop simulations.	[5]	Production	NEW: Quality assurance runs
[…] incorporating their needs into the product structure, functions and aesthetics […]	[39]	Sales	Targeted Reaction to customer needs
Mass personalisation depends on enterprise logistics service, so not only the personalised product but also personalised supply chain management (SCM) should be considered. The adaptability and unpredictability of product designs become essential for mass personalisation	[49]	Sales	Targeted Reaction to customer needs/ NEW: Logistic Effort
Additionally, customers feel they are treated distinctively by the firm	[54]	Sales	Risk of too less product differentiation
The result of this business model is the elimination of two, namely the elimination of inventory, the elimination of intermediaries	[54]	Sales/Procurement	NEW: Logistic Effort/Safety stock (level)
If a customer can tailor one or more of these properties to their specific needs, perceived product quality and thus product satisfaction should increase accordingly (translated)	[56]	Sales	Targeted Reaction to customer needs/Risk of too less product differentiation
In the area of logistics, the number of production orders to be processed is increasing. The total material flow and control effort thus increases considerably	[57]	Sales	NEW: Logistic Effort
In summary, increasing levels of personalization are expected to lead to higher revenues but with diminishing returns	[58]	Sales	Turnover
From the customer's point of view, personalized products can have a number of benefits that increase the willingness to pay (translated)	[18]	Sales	Turnover
Similarly, after-sales teams can find difficulties in (1) tracing individual product data throughout its lifecycle, i.e., true BoM, (2) obtaining information on product servicing procedures, and (3) training field service personnel	[39]	Service	Variety of spare parts
The commissioning and field service procedures for each product will be different, thus requiring up-to-date product specifications, operational manuals and service records, which is a very challenging task in reality because of typical product typebased information storage mechanisms in ERP and after-sales systems	[39]	Product Development/ Service	Amount of coordination & documentation/Variety of spare parts
Mass personalization brings more value to both producers and customers. By supplying customers with customized products, producers can obtain differentiation	[54]	Product development/Sales	Freedom of Design/Targeted Reaction to customer needs/Cannibalization

Table 1. ***Continued***

Quote	Author(s)	Life phase(s)	Effect(s)
The co-design process is not only seen by customers as a way to an end (individual product), but has a symbolic value itself. Schreier (2005) cites the "pride-of-authorship" effect, for example. For customers, the excitement of having created something themselves could be value-creating in itself	[56]	Product development/Sales	Co-design/Risk of too less product differentiation
The high degree of flexibility leads to a constant change in the requirements for the operating personnel. This must be taken into account by intelligent qualification measures at the workplace. To this end, the machine manufacturer provides training and qualification modules as a value-added service that takes into account the current individual level of knowledge of the machine operator and adapts accordingly.(translated)	[59]	Production/Sales/ Service	Training needs for staff
Potential products that can be personalized are those tailored to consumers" body and esthetic/psychological aspects under the restrictions of manufacturability and safety	[13]	Sales/Production	Targeted Reaction to customer needs/ Parallel Testing
[…] these challenges include a lack of sufficient flow of product information across the organization, […]	[39]	General	
On the one hand, some studies have indicated that a competitive advantage can be gained by offering personalized products	[58]	General	
…			

Holistic Impact Model of modular product families considering personalization (IMF + P)

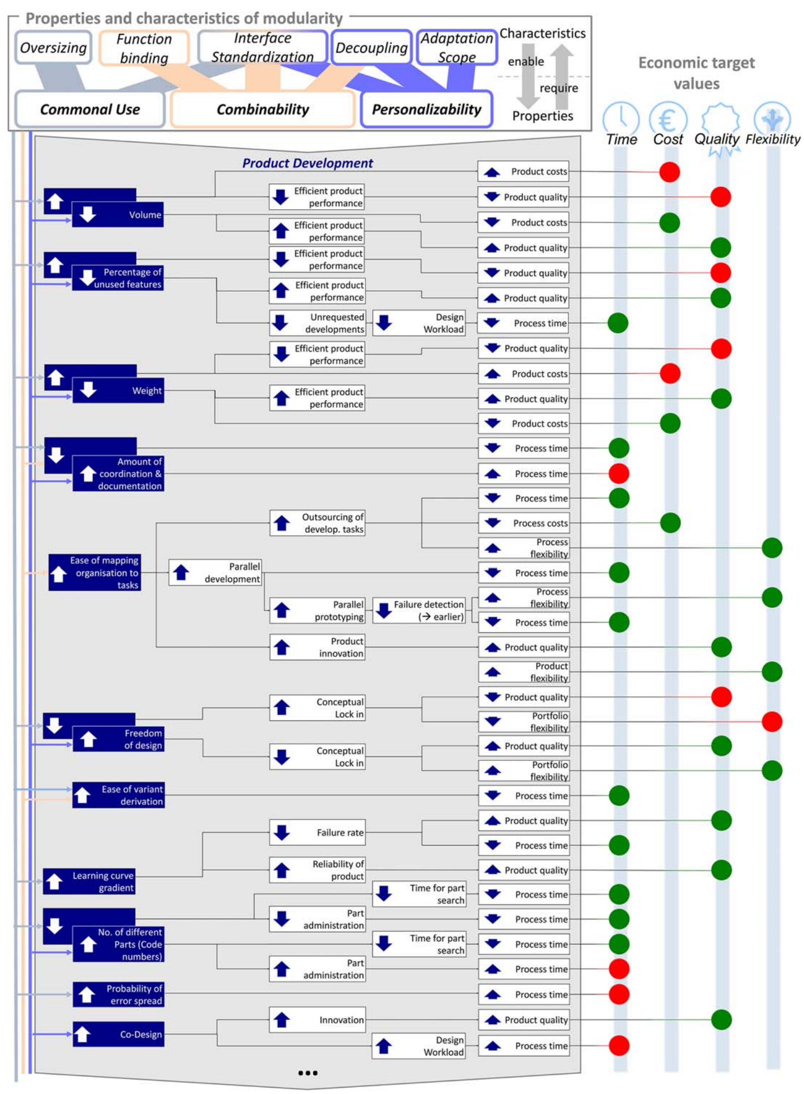

Fig. 14 Holistic impact model of modular product families (IMF + P)—Part 1

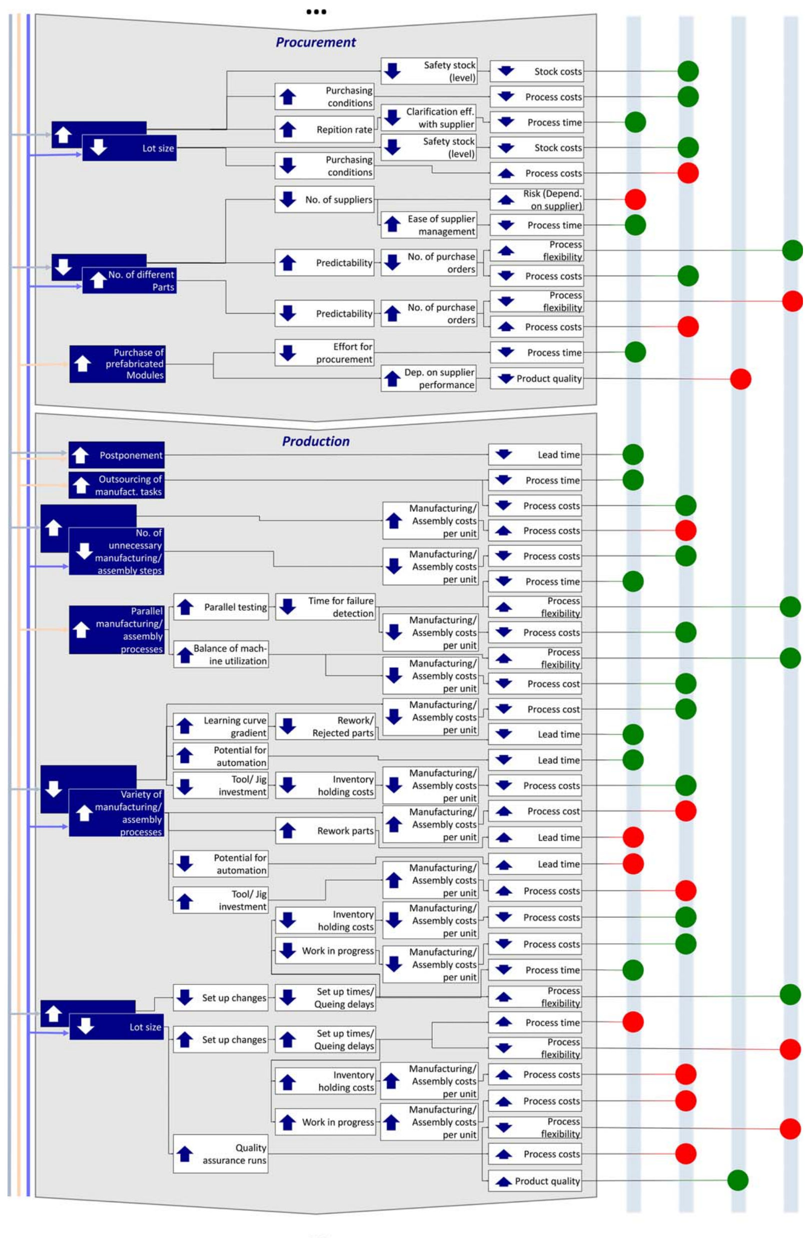

Fig. 15 Holistic impact model of modular product families (IMF + P)—Part 2

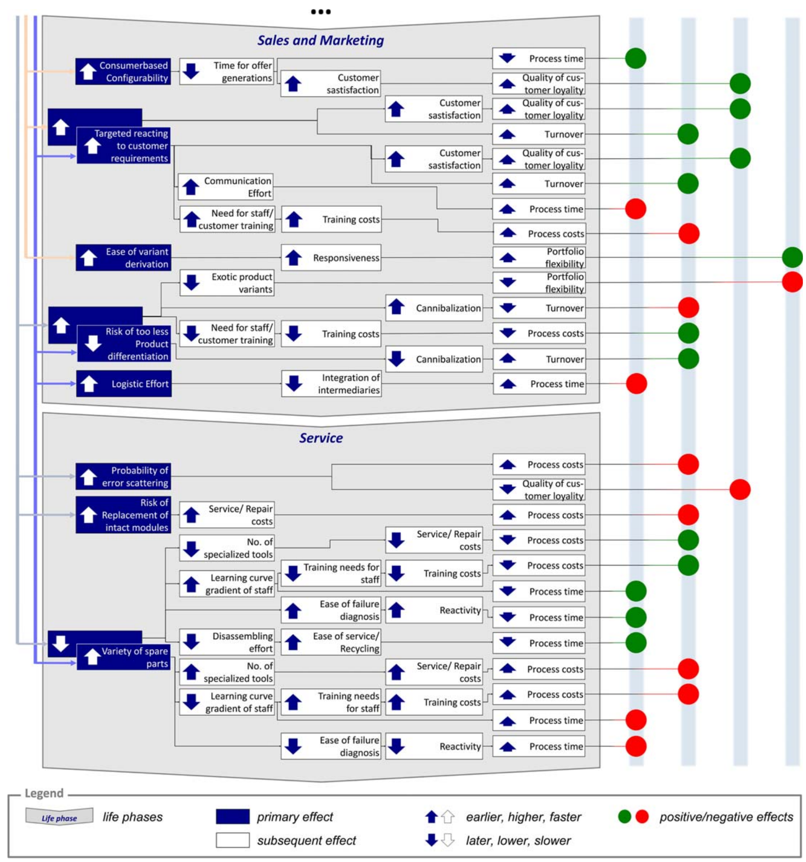

Fig. 16 Holistic impact model of modular product families (IMF + P)—Part 3

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