Analyzing Dependencies between Product Architecture and Module Drivers

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Abstract

A company's business model focuses on delivering personalized products or changing its offering to a Product-Service System impacts the underlying product architecture. Depending on the aim, different product architectures need to be designed. Therefore, modularization utilizing module drivers offers the advantage that additional objectives can be addressed. This contribution identifies module drivers focusing on the architecture design of personalization, collaboration, or PSS, which are not yet known. Analyzing existing literature and empirical findings, dependencies between different module drivers and product architectures are identified. As a result of this contribution, an extended view of module drivers in various product architecture applications is given.

Keywords

Modularization, (Modular) Product Architecture, Product-Service Systems (PSS), Personalization, Modular Systems Design

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1. Introduction

Changing a company's business model to focus on the delivery of personalized products, or changing its offering to a Product-Service System (PSS) due to increasing servitization, impacts the underlying product architecture. Depending on the exact aim, different product architectures need to be designed. An increase in the product variety in terms of individual product variants for each customer or the offering of services accompanying the product often results in a higher degree of internal variety concerning products and processes. Modularization is referred to in the literature as a suitable approach to make this variety manageable in the long term. A wide variety of approaches exist for the actual module clustering, i.e., the skillful combination of components to form modules, such as module clustering based on module drivers [1]. Modularization utilizing module drivers offers the advantage that besides variety management, other objectives such as reducing storage costs or more general economic targets can be addressed [2]. However, which module drivers need to be focused on while designing modular product architectures for personalization or PSS is not yet known. This results in the research question: What dependencies between product architecture and the weighting of module drivers for new trends like personalization, PSS, or systems design?

2. State of the Art

All product variants with a similar area of application, similar function, or similar technology are summarized in a product family [3]. With a modular product architecture for the product family, different product variants can be configured from standardized, commonly used modules, combined with variant and optional modules [4]. However, there is no ideal product architecture, but depending on the company's constraints and the objective of modularization, the modular product architecture can be different [5]. The modularity of a product architecture can be expressed using the characteristics and properties of *commonality*, *combinability*, *interface standardization*, *function binding*, and *decoupling* defined by Salvador [6]. Hackl et al. additionally add the modularity characteristic of *oversizing* [7]. In addition, they summarize the effects of a more or less common modular product architecture or a more or less combinable product architecture in an *Impact Model of Modular Product Structures* [3]. In the model, the effects of the modularity properties *commonality* and *combinability* are presented life-phase by life-phase, linked with subsequent effects to form impact chains, and finally assigned to the economic targets *time*, *cost*, *quality,* and *flexibility*.

Different modularization methods also influence the exact design of the modular architecture [2]. Besides technical-functional modularization methods such as the *Design Structure Matrix* (DSM) [8], Heuristics according to Stone [9], or *Functional Modularization* according to Göpfert [10], there are product-strategic methods such as the *Modular Function Deployment* (MFD) according to Erixon [11]. The *Integrated PKT-Approach for Developing Modular Product Families* combines technical-functional modularization with product-strategic modularization aspects[12]. For this purpose, module drivers are used for product-strategic modularization after a technically functional modularization, for example, the *DSM*. Based on the MFD, a module driver describes a reference point or reason for arranging components together in a module. As part of the *Integrated PKT-Approach*, the generic module drivers are first assigned to the product life phases (see Figure 1, lower left), and company-specific module driver specifications are derived from linking the components of the product to them [13]. All components related to a module driver specification should ideally be combined in a module. This process is supported and visualized by network diagrams, in which the module driver analyzed are shown in the first column, the module driver specifications in the second, the assigned components in the third column, and the final module decision in the fourth (see Figure 1, upper left) [13, 14]. This way, modular structures can be developed life-phase by life-phase, which are then compared, discussed, and harmonized [14]. For discussion, the visualization tool of a *Module Process Chart* (MPC) is used (see Figure 1, right side). Here, the previously defined modular structure preferred by each life phase is depicted, and conflicts can be uncovered and solved to derive a consistent modular product structure.

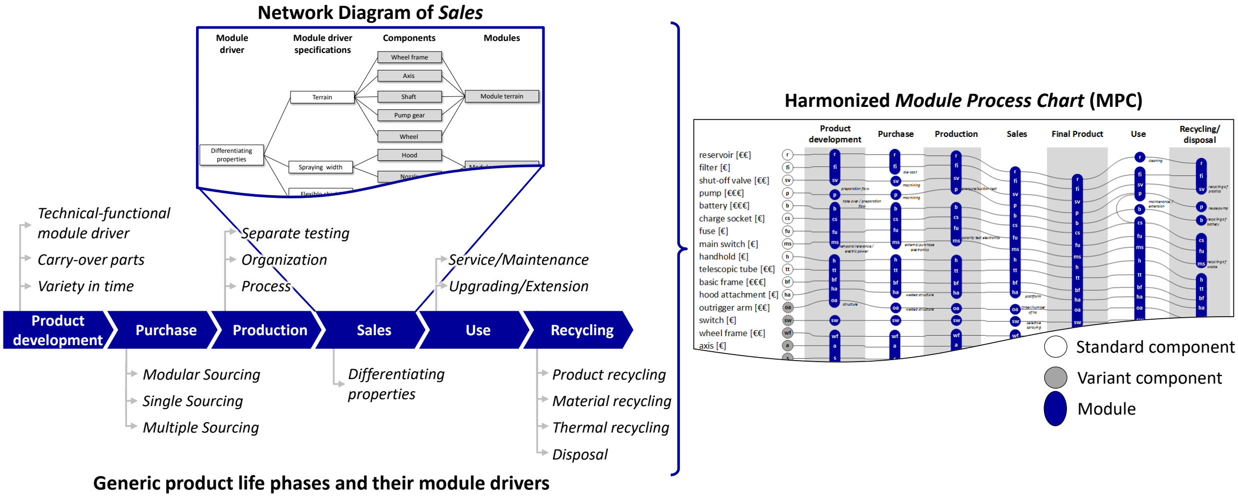

Figure 1: Network diagrams for every life phase (left) are combined in the Module Process Chart (right)

Up to now, the aims set at the beginning of a modularization project could support the compromise finding and weighting of the different module drivers. However, new trends such as PSS or personalization, as well as the necessity of increasingly pronounced interdisciplinary work, have led to new objectives in the design of modular product architectures, which have not yet been taken into account in the literature and for which the weighting of various module drivers and life phases in modularization are not precise.

The trend of personalization describes the adaptation of a product to exact individual customer needs, so that product variants are no longer developed for customer groups on an order-neutral basis but are adapted for individual customers according to their specific orders [15]. A standardized individualization process is recommended to realize individual product adaptations in a complexity-controllable manner [16, 17]. In addition, personalizable modules should be added to the already known standard, variant, and optional module types in the product architecture [18, 19]. So far, however, the literature only describes that personalized modules should be formed. However, it does not offer any support on how to implement this [20]. Although Tan [21] mentions that, among other things, MFD with module drivers "*can be applied to module partitioning for product architectures that include personalized modules with little modification to their techniques*" ([21], page 12/13), however, there is no further elaboration on how the weighting of module drivers changes or to what extent a modular product architecture is influenced by personalization.

Besides the personalization of products described above, companies can also differentiate themselves from competitors by offering product-related services. The combination of products and services is called a PSS [22]. When products and services are designed together, a distinctive characteristic is that services are intangible and produced and consumed simultaneously in contrast to products [23]. There exist a variety of approaches to how PSS can be modularized. These differ in whether they focus on the PSS as a whole or the services [24]. However, the technical-functional approach to module creation is mostly adopted; a module driver concept or other product-strategic approaches are limited to sustainability[25]. Nevertheless, product strategy approaches are quite relevant in the context of PSS since the nature of the PSS has a direct impact on the underlying architecture [26]. This represents a great potential in the modularization of PSS that has been insufficiently exploited so far.

To enable PSS, as mentioned above, and meet the market's complex requirements with better products, many companies are concerned with the improved integration of interdisciplinary structures in their products [27, 28]. This primarily involves the collaboration of different development disciplines, such as mechanics, electrics, software development, fluidics and opts, and, in further examples, optics and others [29, 30]. There is already a corresponding understanding of modularization in many of these disciplines. But a cross-disciplinary view of the holistic design of a modular product system is missing [29]. Since the holistic view of the product system, including all disciplines involved, follows the idea of the development life cycle, a transfer to the subsystem level also results in an advantage for the modularization of cross-disciplinary products. The consideration of cross-disciplinary collaboration and harmonization has not yet been explicitly considered for modularization [31, 32]. Therefore, the possibilities of product-strategic module drivers in a product system context have not yet been sufficiently addressed.

3. Research Problem and Research Goal

Using module drivers for module creation is an established approach [1]. The existing module drivers have been assigned to generic product life phases, e.g., *development* and *production*, for more target-oriented use [2]. However, this generical view is no longer sufficient since the product architectures are becoming increasingly diverse, and an interdisciplinary perspective is becoming more relevant. Although higher-level module drivers such as *organization* are already mentioned in [1], these are not detailed enough.

Another challenge is balancing the module drivers. Since different modules are created depending on the selected module driver, which module drivers should be weighted more heavily for which type of product architecture should also be checked. In summary, the research question posed in the introduction is not yet adequately answered by the current state of the art. It will therefore be examined in detail in the following.

4. Material and Methods

The data basis for this contribution is a systematic analysis of existing publications about module drivers. Here, the focus is on publications highlighting the dependencies between module drivers and different product architectures. Additionally, a workshop-based study with 27 Ph.D. students and industry experts from the field of modularization was conducted at the PAD Summer School[1] to investigate how the modules differ for different types of PSS-based business models. The information from the two analyses is compared and then evaluated concerning the degree to which the business objective influences the relationship between module drivers and product architecture. Finally, the results are used in a case study investigating a Laser Processing Unit.

5. Results and Discussion

Depending on the underlying business strategy and product architecture, the analysis of generic lifecycle combinations and processes must be detailed in module drivers, their characteristics, and weightings. This is shown as an example in Figure 2. Three trends are examined to analyze the dependencies in which particular product architectures are required: Systems Design, Personalization, and PSS.

[1] 5th International Summer School on Product Architecture Design PAD2022, 20.-23.07.2022 in Gothenburg, Sweden.

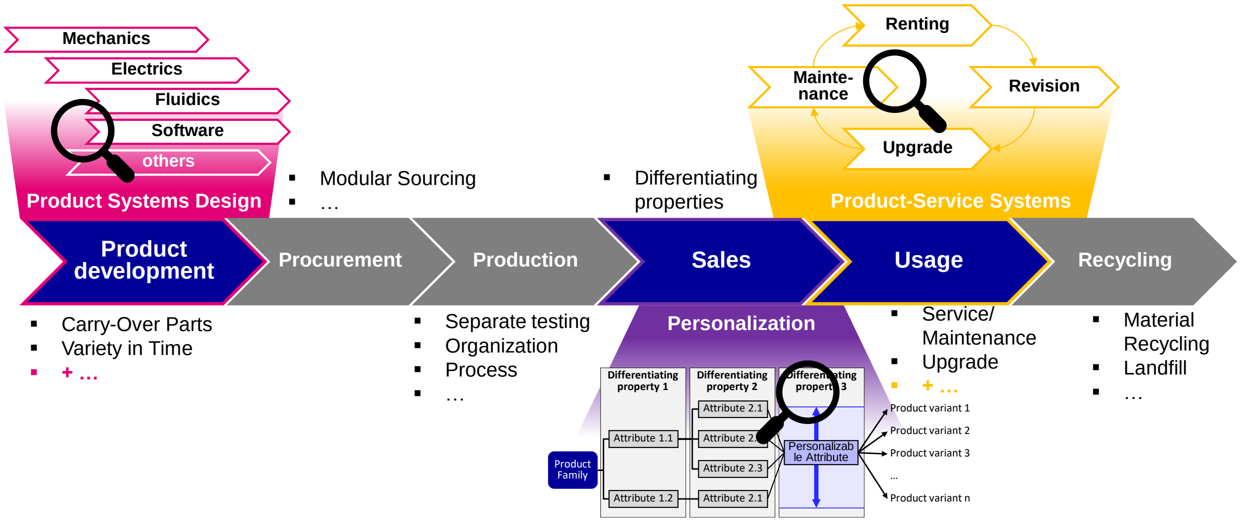

Figure 2: Generic development process with the respective generic module drivers and the analyzed life phases

5.1. Trend-specific module drivers and the resulting product architecture

Considering the trend of personalization in a modular architecture becomes very obvious through the new module type of the personalizable module [19]. In general, to avoid change propagation when the personalizable module is adapted according to individual customer requirements, the aim while designing a modular product architecture considering personalization is to isolate the module as much as possible from other modules which are developed order-neutral. To achieve this, the module driver *differentiating properties* of the sales life phase gets high weight. In particular, the modules emerging from the differentiating properties for which planned personalizable attributes should be kept, harmonized, or adopted by all other product life phases. The different life phases should be oriented to this module definition and design their structures so that the defined module can be considered decoupled in combination with a high degree of flexibility in the processes and workflows associated with the module, a personalization that can be managed in terms of complexity can be made possible. This is shown as an example in Figure 3.

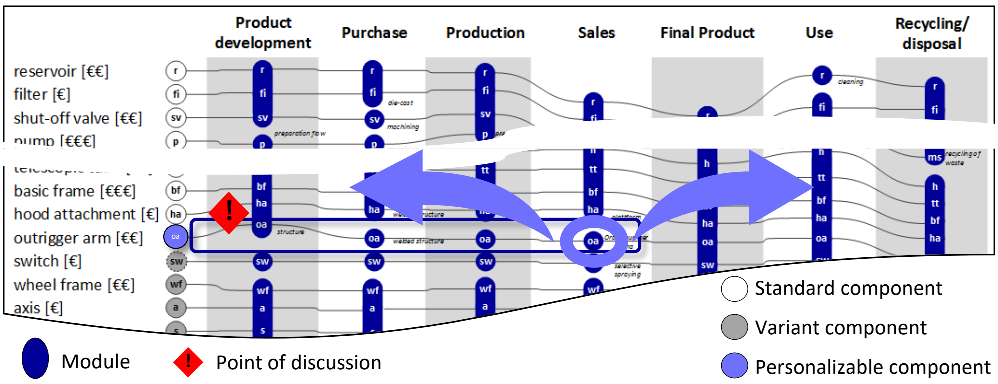

Figure 3: Focus of the MPC when harmonizing considering personalization within the product architecture

While designing PSS, a product- and service architecture are combined. For the development of service architectures, the same approaches as for product architecture design can be used [36]. The consideration of service architectures is an upcoming topic in the research field of product modularity [37]. A significant difference comparing traditional products to PSS is that the priority of the life phases changes for PSS [38]. The relevance of manufacturing costs decreases compared to maintenance costs, so the focus during development shifts to the usage phase. Product modules should be formed in the usage phase to be suitable for providing services. This results in *services* as a new module driver.

Hereafter, the focus is on the effects of PSS on both the module drivers and the module structure of the product components. Due to the increasing importance of the usage phase, the related module drivers should also be prioritized further. In the literature, in addition to the module drivers *upgrade* and *maintenance* already shown in Figure 2, other drivers related to the usage phase are mentioned. Examples of these are *repairability* [39] and *serviceability* [40]. These module drivers have in common that they aim to make products more service-oriented and reduce maintenance and operating costs. Suppose the product and service are considered together. In that case, there are increasingly organizationally motivated module drivers, such as *process*, which in the context of PSS indicates the combination of product and service components that are required to provide defined value-adding processes within a PSS [41].

A study with 27 participants in which network diagrams for the life phase *sales* of a product family of vacuum cleaning robots were developed showed that the module structure is directly linked to the PSS-based business. First, a module structure was developed based on a traditional sales-based business model with only a few services. Afterward, a module structure was designed based on a result-oriented business model, in which customers pay per cleaned area. Without going into details, it was evident that the module structure differs significantly in the two cases. While several small product modules have been created for the traditional sales-based business model, all the product components have been combined into a single module for the result-oriented business model. The differentiation of the offer for different customers is realized for the result-oriented business model via service modules. Similar results were obtained for the other analyzed life phases. Evidence has shown that the type has a PSS direct influence on the module structure of a component.

Module drivers in product system design focus on the collaboration of discipline-specific subsystems that interact with each other in the integrated product. Therefore, discipline-specific designs follow general module drivers, such as *carry-over parts* or *variety in time*, and specific module drivers for the individual development disciplines. For example, with the increasing use of information technology in product architecture design, additional module drivers in the accessory development disciplines are about to be considered [29]. Those Module drivers are not explicitly addressed, e.g., in fluid power and software engineering areas. But there are a variety of considerations for the requirements for the successful development of such systems. Often, these requirements are structured as non-functional requirements (NFR) that provide the framework for system design [33, 34]. Analyzing these in terms of module drivers yields a selection of possible module driver additions. One potential module driver supplement is *interoperability*. This aims in the system thought at the fact that systems can collaborate among themselves and do not hinder themselves [34, 35]. If this non-functional requirement is transferred to the subsystem level, it results in a requirement for forming harmonized modules across different development disciplines in product system design. This potential module driver can be specified, e.g., by *scalability* or *maintainability*. Hence, new life-phase internal reasons arise on which the formation of modules can be oriented. Therefore, the possibility of transferring the product-strategic consideration to the subsystems of the life phase product development and the multidisciplinary designs developed within it emerges.

5.2. Case Study

The analysis results and findings are now illustrated in a Laser Processing Unit. A Laser Processing Unit is developed and used as part of various laser cutting and also laser welding machines. Due to the high proportion of different disciplines, a Laser Processing Unit represents a complex system that requires a high degree of coordination. In addition, the Laser

Processing Unit lends itself to analysis in the PSS context since it is responsible for the primary function of various machine products and can, therefore, also be a component of multiple services. In addition, the Laser Processing Unit also considers personalization, as each customer has different requirements for their cutting or welding process. This diversification can be addressed through personalization. The module structure of the Laser Processing Unit after the harmonization is shown in Figure 4.

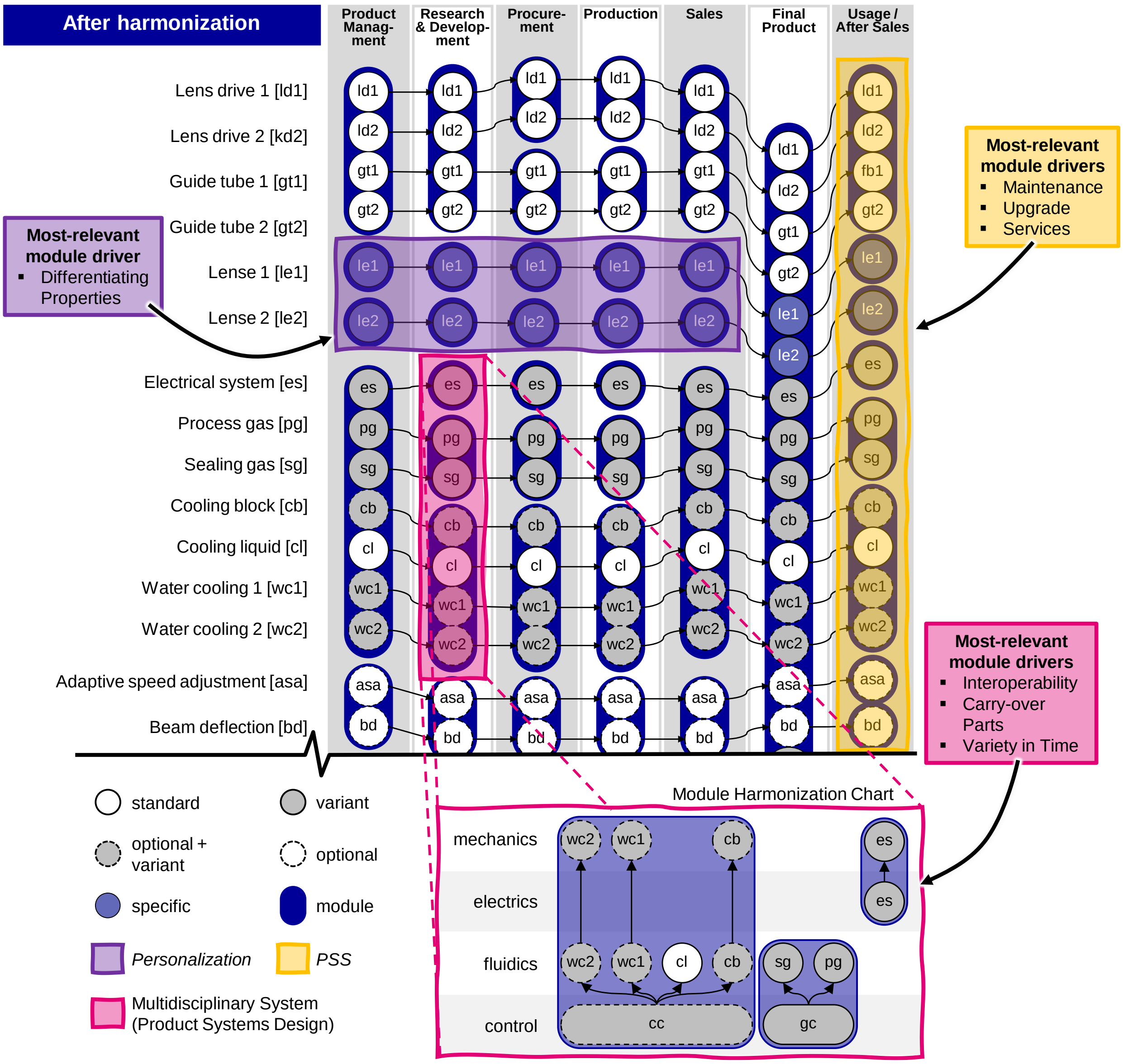

Figure 4: Excerpt from the Module Process Chart of a Laser Processing Unit after the harmonization. Including a Module Harmonization Chart for Product Systems Design according to [29]

The nozzle and lens components could be identified as components that can be personalized as part of an individualized product design. With the aid of a personalized lens, the customer can set individual focal lengths and thus use the laser processing unit following the individual objectives (e.g., according to quality and thickness). The differentiating property *focal length* makes both lenses an individual module harmonized to all life phases. Here the importance of that module driver for personalization can be seen.

For the consideration of PSS, focusing on the life phases of usage or after sales is particularly interesting. In the case of the Laser Processing Unit, the module structure is adapted for leasing the machines. In this business model, the machines are leased to customers for limited periods, including an availability guarantee, and then returned to the supplier, refurbished, and leased to the next customer. For this purpose, the module structure must be particularly maintenance- and adaptation-friendly. On the one hand, it must be possible to replace the modules quickly in the event of damage, and on the other hand, it must be possible to adapt the product to the customer's particular operating conditions. For these reasons, *lenses 1* and *2*, for example, continue to be individual, and *Adaptive speed adjustment* and *Beam deflection* are also individual modules. Since the laser processing unit is to be used for as long as possible in the business model under consideration, the *electrical system* was split off in the module structure so that it can be replaced more easily in the event of further technological developments.

In terms of cross-disciplinary collaboration in the product development lifecycle phase, the Laser Processing Unit provides an illustrative example, as three different development disciplines are involved. In the modularization of the Laser Processing Unit, the disciplines could be harmonized by the module driver *interoperability*, similar to the life phases. This results in synergy effects and improved integration possibilities. Aspects cannot be implemented by the module drivers *Carry-over Parts* and *Variety in Time*. The case study presented improved *maintainability* and *upgradability* through a coordinated module cut that is interoperable across the entire structure.

5.3. Discussion

The case study shows that the three trends of Personalization, PSS, and *Systems Design* influence the module structure and, thus, the product architecture through different focal points, but this does not necessarily lead to conflicts. For example, the module drivers and characteristics relevant for personalization are compatible with the module drivers regarding the adaptation of PSS in the usage phase. If it is a result-oriented PSS in which differentiation occurs via the services, and the product can thus be standardized to a large extent, the personalization potential will shift to the services so that it is also harmonized. Regardless of whether personalization or PSS is involved, the aspect of system design is very relevant for technical innovation. Especially with PSS, a mechatronic product is often required as the basis for the provision of services. As described above, these products must be easy to maintain and adapt during usage. It is, therefore, relevant to upgradeability to have a harmonized module structure for the individual domains, as this reduces the effort required for changes and the probability of errors.

6. Conclusion and Outlook

In summary, it can be stated that due to the expanding considerations of modular product architectures concerning mechatronic and Cyber-Physical Systems, personalization of products, and the extension to PSS with services, more careful consideration of module drivers is necessary. Depending on the objective intended to be addressed by the design of the modular product architecture, different key aspects of module drivers should be selected. Not only the focus on a life phase, which is considered prioritized for a particular architecture is, a possibility, but also the additional consideration of additional module drivers can be a possibility. The different perspectives and foci are not mutually exclusive because combinations of the perspectives presented here are also feasible. The considerations presented here correspond only to selected extracts from potential fields of application of weighted or focused module drivers in the design of modular product architectures. The advantage can be shown from work presented here; the addressed key aspects must be further investigated and specified. For example, in personalization, the customer-relevant product properties relevant to product personalization must be further investigated, just as in

PSS design, the module driver weighting for appropriate use cases and business models requires further investigation. In product systems design, it is also necessary to specify the additional subsystem consideration and the new module drivers potentially emerging and place them in the cross-disciplinary context. Here, interoperability is only a sample of a potential extension of added module drivers for mapping complex multidisciplinary architectures. Thus, there is still some potential for investigations in module drivers, which will have to be addressed in subsequent studies and elaborations.

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