

Towards an impact model of modular product strategies

Luica Pöhlisen✉, Pascal Inselmann and Dieter Krause

Hamburg University of Technology, Germany

✉ luica.poehlsen@tuhh.de

ABSTRACT: The choice of modular product structure strategies has far-reaching implications for development, production, and other aspects of the product life cycle. So far there is only limited methodological support for the decision process. This contribution proposes a conceptual impact model that illustrates the relationships between modular product strategies, induced effects, and resulting economic targets. The proposed impact model supports the decision making process in the early product development stage and serves as a basis for further methodological development.

KEYWORDS: product development, modularisation, product architecture, product architecture strategies

1. Motivation

The product architecture is determined early in the product development phase. This requires thorough consideration, as this decision and its associated consequences are of central importance for the entire product creation and usage. The product architecture influences not only the development of the product, but also procurement, subsequent production, and other life cycle phases, up to recycling. Furthermore, different management processes are shaped by the choice of product architecture (Richter et al., 2016; Krause & Gebhardt, 2023). In addition, the chosen product architecture has an influence on economic targets such as time, costs, quality, and flexibility (Krause & Gebhardt, 2023). Consequently, various aspects and possible effects must be taken into account when choosing the product architecture.

Modularization has established in research and industry as a possible strategy for managing variant-induced complexity (Schuh et al., 2017). Modularization enables a reduction in internal variety while maintaining the external variety offered to customers. Furthermore, various advantages of modular product architectures have already been outlined in the literature, including increased reuse, improved development and production processes, shorter time-to-market, and the possibility of more efficient product maintenance and further development (Ulrich, 1995; Ehrlenspiel et al., 2020; Krause & Gebhardt, 2023).

Different modular strategies can be pursued in the development of modular product architectures. Which strategy is suitable in a specific case depends on the product range under consideration, the corporate strategy, the market position, and other factors (Schuh et al., 2014; Pashaei & Olhager, 2019). Various methodological approaches exist in research for pursuing such strategies. Krause and Gebhardt fundamentally distinguish between common module, modular kit, and platform strategies for modular product structure strategies, each with different objectives and advantages (Krause & Gebhardt, 2023).

In this context, this article outlines an approach to developing a model that (1) distinguishes between modular product architecture strategies at the structural level and (2) formalizes the corresponding impact chains across various life phases. This provides methodological support for decision-making when choosing a modular strategy and shows the effects of the strategies on the company.

2. Research background

Growing awareness of the advantages of modular product architectures has led not only to increased use of the term in literature. The proportion of modular products and the degree of their modularity are also increasing in industry (Burggräf et al., 2019; Mertens et al., 2023).

2.1. Modularization as a strategy for defining product architecture

Modularization is a strategy established in industry and research for managing variant-induced complexity (Schuh & Riesener, 2018). In general, the process of modularization begins with the decomposition of a product into its individual components. Based on analyses of the components, their interactions, and other strategic aspects, the components are then grouped into modules (Schwede et al., 2022). Thus modularization is the decomposition of an overall system into clearly defined independent units, known as modules. The individual modules are decoupled from each other and each fulfil (sub-) functions of the overall system (Göpfert, 1998). In order to achieve a high degree of modularity the characteristics such as decoupling, function binding and interface standardization should be taken into account (Krause & Gebhardt, 2023).

There are various approaches for modularization in the literature. These can be categorized as technical-functional and product-strategic. Methods such as the Integration Analysis of Product Decompositions by Pimpler and Eppinger (1994) or the House Of Modular Enhancement method by Sand et al. (2001) are technical-functional methods. In these, the product is decomposed into its components, the interfaces and interactions between the components are analysed with regard to various criteria, and then a modular product architecture is designed based on the previous analysis (Krause & Ripperda, 2013). Methods such as Modular Function Deployment by Ericsson and Erixon (1999), the method by Yu et al. (2011) or the Eco-modular product architecture identification and assessment for product recovery method by Kim and Moon (2016) also decompose the product into its components, but then evaluate each component individually with regard to various modular drivers and then, again based on the evaluation, develop a modular product architecture. These are called product strategic methods (Krause & Ripperda, 2013). There are also methods, such as the Integrated PKT Approach, which represent a combination of technical-functional and product-strategic (Krause & Gebhardt, 2023).

Modularization can have various effects. These can be both technical and economic. For example, development times can be shortened because modules can be developed in parallel or component design can be reused. In addition, flexibility in the product portfolio is increased, enabling companies to respond more quickly to market and customer requirements. Modularization also facilitates maintenance, and the replacement of modules reduces both maintenance time and the associated costs (Fixson, 2006; Abdelkafi, 2008; Boer, 2014; Schwede et al., 2022; Krause & Gebhardt, 2023). Due to the different methods of modularization and the associated different focus aspects, the effects of each type of modularization vary. Furthermore, Krause et al. (2023) distinguish between possible modular product structure strategies within the topic of modularization, namely common module strategy, modular kit strategy, and platform strategy, which also lead to different effects. In the following, the term product architecture is introduced and modular product architecture strategies are presented.

2.2. Product architecture strategies

The terms product structure and product architecture are often used as synonyms in the literature (Herbertsson, 1995; Kissel, 2014). Herbertsson (1995) define product structure as the structured composition of a product consisting of its components. Pimpler and Eppinger (1994) define product architecture based on the definition by Ulrich and Eppinger (1994) as the definition of the architecture of a product as a system whose decomposed elements are organized in blocks. Furthermore, Ulrich (1995) defines the assignment of functions to the physical components of a product as part of the product architecture. Based on Ulrich's (1995) definition, Martin and Ishii (2002) define that the architecture must contain an arrangement of functional elements, a representation between function and structure, and interactions between the components in order to be considered architecture. Krause and Gebhardt (2023) describe the product structure as the physical definition of the product. Together with the functional definition of the product in the functional structure, this results in the product architecture.

Various product structure and product architecture strategies have been identified in the literature. Schuh and Riesener (2018) classify product architecture types as functional-modular, modular, integral,

and physical-modular. Ulrich (1995) also identifies different product structures: integral, modular slot, modular bus, and modular sectional. Krause and Gebhardt (2023) highlight the modular product structure strategies of common module strategy, modular kit strategy, and platform strategy.

Based on the definitions presented, the following definition is used in this paper: *Product architecture* results from the interaction of the functional structure with the product structure. While the functional structure describes the logical organization of functions, the product structure determines the physical units in which the functions are implemented. The combination of both perspectives results in the product architecture. The strategies considered in this paper common module, modular kit, and platform strategies take into account both the functional structure and the product structure. Henceforth, these are referred to as product architecture strategies.

The *common module strategy* focuses on the systematic reuse of modules across the entire product range. The aim is to reuse the same modules in different products, thereby maximizing economies of scale and standardization potential. Krause and Gebhardt (2023) clearly distinguish the concept of the *common module strategy* from the common part strategy, which focuses on part standardization. Ehrlenspiel and Meerkamm (2017) define common parts as parts that occur multiple times in the same product and compare this to repeat parts. These are parts that are used (repeatedly) in both product A and product B. According to Krause and Gebhardt (2023), a common module contains several components. The *common module strategy* allows existing modules to be used in future product development. For this, the modules are usually smaller and have a lower range of functions in order to increase the probability of these modules being used widely. In contrast, the *platform strategy* is characterized by the idea of creating a usually large module (the platform) that is used in all variants of the respective product family and thus forms the basis for different product variants. The platform is therefore a standardized module that covers the components that occur in all product variants of the respective product family. Robertson and Ulrich (1998) define the platform as a collection of shared resources that are used by different products. Components, processes, knowledge, but also people and relationships can be considered resources. If the same components are specifically standardized and used across several products, Ehrlenspiel et al. (2020) refer to this as a platform. According to Krause and Gebhardt (2023), the *modular kit strategy* is a compromise between the *common module strategy* and the *platform strategy*. The aim of the *modular kit strategy* is to represent variety both within a product family and across product families with as few components and modules as possible.

Due to the different objectives pursued by the various modular product architecture strategies, the resulting effects vary accordingly. Existing approaches for representing and visualizing the possible effects in this context are presented in the following.

2.3. Approaches and models for visualizing effects of modularization

Richter et al. (2016) analyse various options for supporting designers in selecting a suitable product architecture concept depending on the resulting effects. The focus here is on the functions.

From the perspective of complexity management, Schuh et al. (2017) develop methods for the further development of product architectures. The focus here is on maintenance costs and change management.

Albers et al. (2015) examine how changes in the technical system of product generations will affect this, and this is reflected in the product generation development model. In order to create an interface between product development and process management, the integrated product development model (iPeM) has been further developed (Albers et al., 2016). Furthermore, the further development of product portfolios through strategic anticipation is being addressed in order to make construction kits more future-proof (Albers et al., 2022).

The impact model for modular product families (IMF), which was developed on the basis of a literature analysis and proven and expanded in industry, shows the possible effects of modularization, organized according to the life phases product development, procurement, production, sales & marketing, and service. The effects are classified into primary and secondary effects (consequential effects) and form resulting impact chains. Furthermore, the IMF shows the influences of the chains on the economic target time, costs, quality, and flexibility (Schwede et al., 2022). In addition, there are key indicators for the individual chains in order to be able to evaluate the effects not only qualitatively but also quantitatively (Greve et al., 2022).

The Product Architecture Strategies and Effects (PASE) Matrix was also developed based on a literature analysis. It shows the linkages between a total of 38 strategies and 271 effects. Users can select strategies for which the possible effects are to be shown, or alternatively select possible effects and obtain the corresponding strategies. For example, the matrix can be used to show possible effects for the strategies “Develop a new modular architecture,” “Decreasing the degree of coupling in a design,” or “Use interface standardization” (Rice et al., 2024).

While the advantages of modularization and different methodological approaches for the development of modular product families are recognized in research, there has been a lack of clear reference between theoretical strategies and their practical impact on business processes. In particular, there has been a lack of methodological support for the choice of the underlying modular product architecture strategy. This research gap forms the starting point for the following problem definition.

3. Problem definition

There is a broad consensus in the literature that modularization brings various advantages for companies (Fixson, 2006; Schuh & Riesener, 2018; Ehrlenspiel et al., 2020; Krause & Gebhardt, 2023). At the same time, it is emphasized that the product architecture is already defined in the early phase of product development, but has far-reaching consequences and effects for the respective company, which may only become apparent much later (Richter et al., 2016; Greve et al., 2020; Krause & Gebhardt, 2023).

For a well-founded evaluation of modular product architectures, it is necessary to consider both the direct perspective of product development and other perspectives such as the following procurement, production, and up to recycling. In this way, the actual organizational and economic effects of the respective modular product architecture strategy can be comprehensively captured.

Current approaches have focused primarily on designing individual modules of the product within a product architecture strategy. While this allows technical relationships to be analysed, the overarching strategic effects of different product architecture strategies on business processes and economic targets are mostly not taken into account.

The IMF represents a validated approach in research and industry (Schwede et al., 2020, 2022). It already shows possible effects of developing modular product families across different life phases and illustrates the impact of modularization on economic targets. However, these are generic effects of developing modular product families. The differences in the effects of the various modular product architectures are not shown. Consequently, the IMF does not support the choice of a modular product architecture strategy. Furthermore, the IMF is a static model, which means that dynamic adaptations to the IMF are not possible and, as a result, the effects of different decision alternatives cannot be simulated.

Different product architecture strategies are shown in the PASE Matrix (Rice et al., 2024), but the approach has some conceptual limitations. The strategies listed in the PASE Matrix are written in a generic way and are combined during data preparation when similar ideas are presented. As a result, there are no clear distinctions between the strategies, meaning that some synonyms exist and strategies with overlapping content are present in the PASE Matrix. Furthermore, no concrete distinction is made between different modular product architecture strategies; instead, several are merged without differentiating them conceptually. This means that the level of strategies remains abstract and without clear separation in terms of content. In addition, it is also a static representation, meaning that generic relationships between strategies and effects are shown, but no quantitative evaluation or dynamic adjustments to company-specific conditions are possible.

Due to the different objectives that the different modular product architecture strategies follow, the resulting effects vary accordingly, thereby influencing economic targets in different ways. Current models do not fully represent the effects of modular product architecture strategies and do not allow for a comprehensive analysis of the consequences of a strategy choice across the product life cycle. Consequently, one aspect that has been not sufficient investigated so far is the systematic selection of the underlying product architecture strategies for modularization. There is a lack of founded, methodical approaches that allow different product architecture strategies to be evaluated in a comparable manner, their effects on technical, organizational, and economic targets to be assessed, and their suitability for specific corporate contexts to be determined. Such support contributes significantly to companies being able to systematically make use of the potential offered by modularization.

This leads to the following research questions:

1. How can the evaluation of different product architecture strategies be supported methodically?
2. How can the effects and interdependencies of modular product architecture strategies be visualized through a modelling approach?

To answer the research questions, the following chapter presents a generic solution concept for the development of an impact model. This model is designed to illustrate the effects of different modular product architecture strategies and their impact on economic targets, and builds the foundation for a simulation-based analysis of various decision alternatives.

4. Towards an impact model of modular product architecture strategies

Although various approaches discuss and evaluate modular architectures or the effects of modularization, existing models do not differentiate between and compare modular product architecture strategies with regard to their impact the specific strategies have on the resulting product architecture and therefore on the economic targets. The aim of this paper is therefore to present a conceptual approach for a generic impact model that describes the possible effects of the selected product architecture strategies and their impact on economic targets. Integration into a simulation-based model offers the possibility of taking uncertainties and dynamic influencing factors into account, thereby providing realistic decision support.

4.1. Fundamental approach and purpose

The impact model is supposed to illustrate the effects of modular product architecture strategies. The solution concept will focus on the three modular product architecture strategies: *common module*, *modular kit*, and *platform strategy*. These strategies have different design objectives and therefore cause different effects throughout the product life cycle. The model to be developed should systematically record the possible effects, illustrate their relationships, and highlight their impact on economic targets. The model should be used as a framework for systematically mapping relationships between strategic decisions, technical and organizational effects, and economic consequences, thereby creating a founded basis for strategic decisions in the early phase of product development.

4.2. Concept and structure of the impact model

The impact model of modular product architecture strategies (IMS) is intended to map the effects from the strategic decision to the economic targets as a causal relationship. Here, impact chains are to be structured into four areas and linked to each other via causal relationships.

The impact model initially involves selecting a product architecture strategy, which forms the starting point for all further interdependencies. This strategic decision shapes the modularization principles and structural characteristics of the product architecture, such as the degree of standardization or the frequency of reuse (Krause & Gebhardt, 2023). Strategies result in effect chains consisting of three logically sequential elements: primary effects, secondary effects, and economic targets.

The product architecture strategies, which represent the input of the IMS, describe the strategic orientation of the respective modularization and define the basic principles of product architecture. Examples of this are the use of common components, the development of modular kits, or the definition of a platform for the entire product family. The resulting primary effects cover the direct effects of the chosen strategy. The secondary effects result from the primary effects. The economic targets represent the result of the effect chain and represent the evaluation parameters. For this purpose, the model should include the targets of time, cost, quality, and flexibility. These targets can influence each other and are often contradictory, which should be made visible by the IMS.

The causal dependencies of the areas mentioned should be described in the IMS and visualized in the form of impact chains. It should also be shown that different effects may not only be caused by one strategy, but can arise from two or all three strategies. In addition, it should be shown that the intensity of the effect or the intensity of the impact on the economic targets can vary depending on the strategy, even if the effect is the same. Figure 1 shows an example of this.

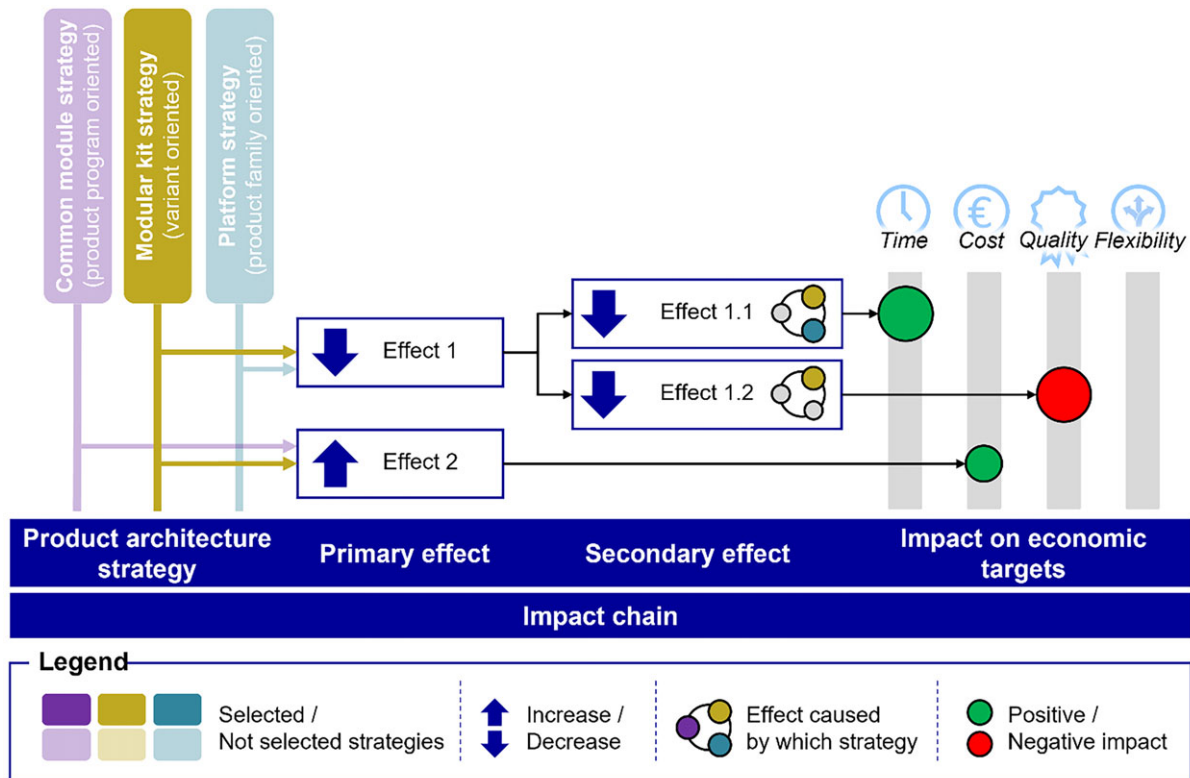


Figure 1. Exemplary chains of effects of modular product architecture strategies

Figure 1 shows two chains of effects. The causal relationship between product architecture strategies, primary and secondary effects, and economic targets can be seen.

Each product architecture strategy is assigned a color for recognition purposes. When a strategy is selected, it is highlighted and the others are presented less intensively. The example here shows three chains of effects when selecting the *modular kit strategy* (light brown). The *modular kit strategy* results in possible primary effects. Here, Effect 1 and Effect 2. Primary effects may result in secondary effects. Here, Effect 1.1 and Effect 1.2 result from the primary effect Effect 1. The secondary effects in turn have an impact on the economic targets. In this case, Effect 1.1 result in a reduction in time (green circle) and Effect 1.2 result in lower quality (red circle). As a further example, the Effect 2 does not lead to a secondary effect, but results directly in a reduction in costs (green circle).

Furthermore, it is necessary to illustrate which effects could also occur if a different strategy were chosen, in order to be able to compare the strategies with each other. There for it is shown that the primary effect Effect 1 can also be achieved by the *platform strategy* (turquoise). In this example, the *common module strategy* (purple) would lead to the primary effect Effect 2, but not to Effect 1. Because various strategies can lead to different secondary effects from the same primary effect, a color scheme is added to the secondary effects to show what architecture strategy they are based on. Consequently, it is shown that the Effect 1.1 can also be achieved by the *platform strategy* (turquoise) but the Effect 1.2 not. The color coding allows effects that can be caused by several strategies to be identified.

Further the impact on the economic target variable may vary in strength depending on the strategy. For this purpose, the green or red circle is shown correspondingly smaller or larger. Consequently, it can be seen that the *modular kit strategy* selected here has a lower positive impact on costs through the primary effect Effect 2 than the *common module strategy*.

The linear representation from left to right allows the impact chains to be understood intuitively. They support the understanding that the choice of product architecture strategy as the trigger for the impact chains leads not only to primary effects but also to secondary effects and influences the economic targets. Since the effects of modular product architecture strategies do not occur in isolation in product development, but have an impact throughout the entire product life cycle, the model should include a life cycle-oriented approach. Different effects can dominate in each life phase, such as cost savings in procurement or reduction of assembly time in production. Figure 2 shows a schematic representation of the planned IMS, including consideration of different life phases.

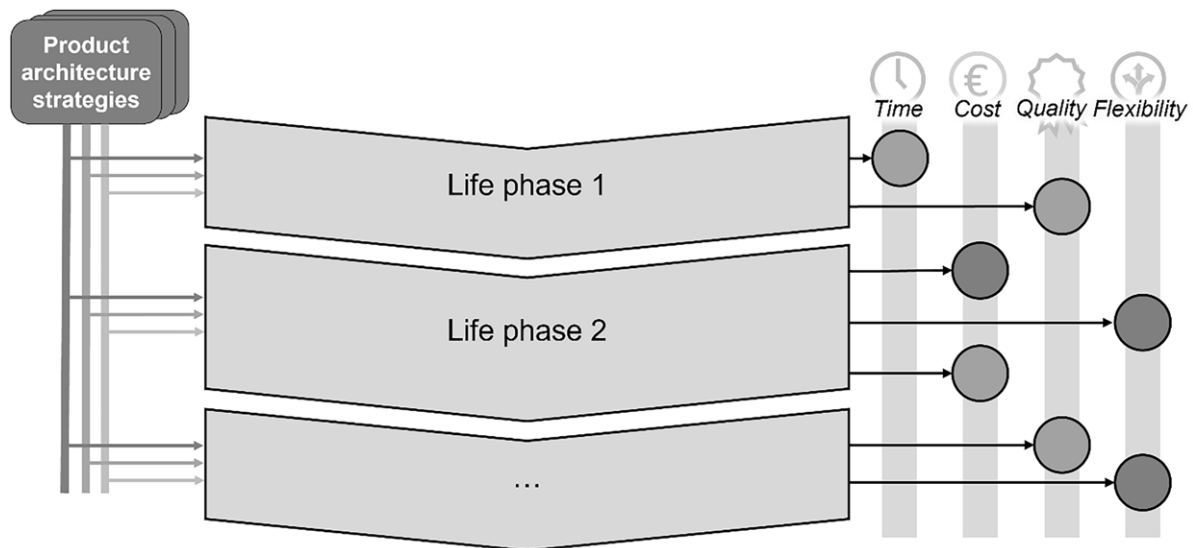


Figure 2. Schematic structure of the IMS, based on Schwede et al. (2022)

Figure 2 shows that the life phases along the life cycle should be presented hierarchically. In addition, the impact chains resulting from the three product architecture strategies should be presented within the respective life phase.

Additionally, contingency parameters should be included to account for the dependencies of the effects of company and market constraints. These include, for example, the existing organizational structure, the current product architecture, given standardizations and established platforms, market and demand volatility, and the company's strategic objectives. By integrating the constraints, the model can be applied more flexibly to different situations. These therefore form the basis for simulations of the effects of choosing a modular product architecture strategy.

4.3. Approach for developing the impact model

Developing such a model requires a step-by-step methodological approach. The first step should be a systematic identification and classification of effects associated with modular product architecture strategies. This requires a comprehensive literature review focusing on modularization, product architecture design and modular product families. One challenge is the fact that the strategies common module, modular kit and platform are not always explicitly referenced in the literature. In many publications the effects are generally described in the context of modularization without distinguishing between the different architectural strategies. In other cases, similar concepts are described using other terminologies. For example, platform-based development, component reuse or product family design. In addition, the identified effects should be supplemented with results from existing empirical case studies or industry examples to ensure that the model is relevant to practice as well as theory.

The next step is to map the relationships between the strategies, effects, and target variables in the form of impact chains and assign them to the life cycle phases. In this step the effects should be differentiated according to whether they are strategy-specific or strategy-overlapping. This means whether they are predominantly associated with one strategy or occurring across multiple strategies but with different intensities. If the same primary effect can result from several strategies, the model should show differences in the intensity of the effects. This differentiation is crucial in order to enable a comparative evaluation rather than showing general effects of modularization.

Afterwards the impact chains should be assigned to specific life phases such as product development, procurement, production and so on until end of life. This makes it possible to see which effect occurs in which phase of the product life cycle and how primary effects lead to secondary effects. The result then shows the causal structure of strategy, primary effect, secondary effect, and economic target variable in the form of impact chains in the different life phases.

Finally, the effects of contingency parameters that influence the magnitude or direction of effects such as the corporate strategy, the existing product portfolio, or demand volatility. These parameters are not

modelled as primary drivers of effects, but as variables which adjust the impact intensities in the model. These parameters enable the model to be applied flexibly to different corporate situations, forming the basis for future simulation scenarios.

5. Conclusion and outlook

The aim of this paper is to highlight the importance of choosing a modular product architecture strategy and to address the existing research gap with regard to systematic support in choosing a product architecture strategy. An analysis of the current state of research shows that, although different methods of modularization exist and the advantages of modular product architectures are well known, an approach for comparing and evaluating *common module*, *modular kit*, and *platform strategies* is not yet available. In particular, there is a lack of models that present the economic effects in a holistic and comprehensible manner for the modular product strategies.

This paper therefore contributes by explicitly distinguishing modular product architecture strategies at the architectural level and presents a conceptual approach for a generic impact model. The proposed model describes causal relationships between the choice of strategy, the primary and secondary effects, and the economic targets of time, cost, quality, and flexibility. The structure of the model is built from left to right, thus demonstrating the causality of strategic decisions and their corresponding effects in a transparent and understandable way. The IMs presented in this paper represents a conceptual modelling framework. While the structural logic of strategy, effects and economic target as an impact chain is defined, the full operationalization, parameterization and quantitative implementation remain to future work. Once the IMS is implemented, the IMS must be validated for example through empirical case studies or an industrial application. Such validation will be essential to demonstrate its robustness and decision support value.

The expected added value of the IMS is based on the successful application of comparable impact models found in existing literature such as the IMF and its extensions. These validated approaches demonstrate that structured representations of effects of modularization can enhance transparency and support decision making. The IMS builds upon these by extending the perspective to modular product strategies and addressing a strategic decision layer that has so far received limited modelling attention.

By integrating contingency parameters, the model can be flexibly adapted to different business situations, thereby supporting informed decisions in the early stages of product development.

In future research the model should be implemented in a simulation-based environment in order to quantitatively analyse uncertainties and interactions. This will enable the effects to be assessed not only qualitatively but also quantitatively in the future. In the long term, the IMS is intended to support decision-making, helping companies to select modular product architecture strategies in a targeted manner and anticipate their economic impact across the entire product life cycle.

This work therefore lays the foundation for systematically analysing modular product architecture strategies in the future with regard to their interdependencies. The future implementation of the model opens up the potential to compare strategic product architecture decisions and therefore provide long-term support for the modularization of product programmes in industry and research.

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