Towards a Framework for the Continuous Decision-Making Concerning Variety-Induced Cost of Complexity in the Product Generation Development Process

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Abstract: Existing approaches for considering and evaluating product family concept alternatives in terms of variety-induced cost of complexity focus only on the subsequent evaluation of total concepts and are not integrated into the product generation development process. In response to escalating product complexity and its associated costs, a comprehensive framework for integrating variety-induced cost of complexity as a target value into the product generation development process is to be developed. Emphasizing a continuous consideration of variety-induced cost of complexity in the early phases of product generation development, the framework aims to support the cost target-orientated development of modular product families. To avoid a cost and time intensive subsequent evaluation regarding cost of complexity, the framework ensures the proactive management of these throughout the product generation development, enabling more strategic and cost-effective design decisions.

Keywords: cost of complexity, product generation development, cost assessment, complexity cost, product family evaluation

1 Introduction

The increasing global competition of products with small batch sizes and high product requirements leads to decreasing competitiveness and rising cost pressures for manufacturing companies. Companies often respond to decreasing competitiveness with an increasing variety of products and individualized solutions for their customers (Ripperda and Krause, 2017). The resulting processes finally lead to variety-induced cost of complexity in the affected companies, in order to manage the increased internal variance (Ehrlenspiel et al., 2014; Krause and Gebhardt, 2023; Ripperda and Krause, 2017; Thonemann and Brandeau, 2000).

To remain competitive in the global market in a long term view, variety-induced cost of complexity must be reduced by developing a modular product architecture, which allows the necessary product variance to be offered at a competitive price level (Ulrich, 1995). To showcase the savings achieved through the development of modular product architectures, the variety-induced cost of complexity must be quantified and documented.

For targeted reduction of variety-induced cost of complexity, it is necessary to integrate these costs as an optimization target in the product generation development process (Mertens et al., 2023; Mortensen et al., 2016). By early consideration and quantification of potentially arising variety-induced cost of complexity, engineers in product generation development can be provided with concrete decision support regarding changes made on the current concepts. Due to the lack of early consideration of cost impacts, concept decisions in companies regarding complexity reduction, and thus cost of complexity reduction, are made without a concrete cost data basis.

It has been shown that variety-induced cost of complexity must be continuously and concurrently considered during the product generation development process to target them effectively through the development of a modular product family (Ridder et al., 2023). By taking variety-induced cost of complexity into account at an early stage and sub-concept level, process costs in the concept phase can be reduced significantly while simultaneously targeting the potential cost of complexity (Rathnow, 1993). In this context, considering the sub-concept level means integrating the variety-induced cost of complexity within the concept development of a distinct part of the overall product. The overall concept development of a product can be divided into various sub-concepts to be developed, such as individual functional units of the product.

Furthermore, it has been shown that existing methods for developing modular product families do not sufficiently consider potential variety-induced cost of complexity in their approaches (Ridder et al., 2023). Methods for considering and evaluating product family concept alternatives in terms of variety-induced cost of complexity focus only on the subsequent evaluation of total concepts and are not integrated into the product generation development process (Ridder et al., 2023).

2 State of the art

In the following chapter, the current state of the art regarding the integration of variety-induced cost of complexity into the product generation development process is presented. For this purpose, Chapter 2.1 outlines relevant approaches that focus on the consideration of costs and cost of complexity in product development. Chapter 2.2, on the other hand, elaborates on approaches to support the product generation development process. In particular, methods for developing modular product families are presented here.

2.1 Methods for cost assessment in product development

In literature, there are numerous methods focusing on the consideration and assessment of costs associated with product architectures. These approaches particularly emphasize the inclusion of cost of complexity induced by variants. As part of the integrated PKT approach for developing modular product families (Krause and Gebhardt, 2023), the method *Methodical Support for Cost-Based Selection of Modular Product Structures* by Ripperda offers methodical support for the cost-based evaluation of alternative product family concepts regarding cost of complexity induced by variants (Ripperda and Krause, 2017). The calculation of these cost of complexity is based on *Time Driven Activity Based Costing* (TDABC) (Kaplan and Anderson, 2009) and is divided into three phases: *Cost Forecast*, *Cost Evaluation*, and *Cost Reduction*. This methodical support particularly focuses on costs arising from the variety of the internal product diversity. A similar approach for calculating variety-induced cost of complexity based on *Activity Based Costing* (ABC) is presented by Bauer in *Complexity costs evaluation in product families by incorporating change propagation* (Bauer et al., 2015). Using ABC, process times and thus resulting process costs for component changes are determined. Based on these results and the identification of existing variety-induced change drivers in the product architecture, cost of complexity of the product lifecycle are calculated. In addition to these methods, *Activity-based costing as a method for assessing the economics of modularization* also relies on the ABC analysis to evaluate individual product architecture concepts for their profitability. The potentially arising process costs of individual product architecture concepts with varying degrees of commonality can thus be evaluated and selected based on the potential total costs (Thyssen et al., 2006).

The approach *Calculation and Allocation of Complexity Costs Using Process Data Mining* by Riesener enables the derivation of emerging cost of complexity through the integration of a process data model and the existing product portfolio (Riesener et al., 2019). Through process-oriented cost accounting, arising costs are allocated to individual components at the bill of materials level and made be visible. Given the volume of data to be considered, Process Data Mining is used. By allocating costs at the bill of materials level, cost of complexity regarding existing variants can subsequently be derived and adjustments to the product portfolio can be made.

Another method for evaluating and adjusting the existing product program is presented in *Calculation of Complexity Costs – An Approach for Rationalizing a Product Program* by Hansen (Hansen, 2014). This approach supports a targeted cost analysis of the existing product program to remove unprofitable product variants. The consideration of cost of complexity is applied at the level of the entire product program. By determining the sales of individual product variants and identifying the resulting product costs on the corporate side, profitable and unprofitable product variants within the company are identified. By eliminating the unprofitable variants from the product program, the associated variety-induced cost of complexity is automatically reduced.

Approaches for the qualitative evaluation of modular properties regarding their cost implications are provided by the *Impact Model of Modular Product Families* (IMF) (Hackl et al., 2020) and the approach *Cost-oriented evaluation of modular product architectures* by Skirde (Skirde, 2015). The IMF, part of the *integrated PKT approach*, enables the assignment of modular properties to effects on economic targets using identified causal chains. By linking modular properties to economic target values such as costs or process time, the impact on variety-induced cost of complexity can be demonstrated (Schwede et al., 2022). Skirde enables a forecast of cost impacts of individual product architectures. For this, an existing product is categorized into one out of six levels of modularization. Based on this classification, previously determined costs are extrapolated to the remaining five levels of modularization. Based on this extrapolation, the effects of different modularization levels on costs can be demonstrated, thereby providing recommendations for increasing the degree of modularity (Skirde, 2015).

2.2 Methods for product-generation development

In the literature, there exist several of methods that support the product generation development process. Particularly, methods that support the development of modular product families are focused here, as the described goals can be achieved through complexity reduction by modularization.

Modularity is a gradual measure, which can be described by the properties of combinability and communal use (Salvador, 2007). Combinability refers to the ability to couple different modules to generate new product family concept alternatives. Communal use targets the strategy of using common parts: Through planned oversizing, modules are developed in such a way that their use across multiple product family concept alternatives, even across product generations, is enabled.

Methods for developing modular product families are based on the following generic structure (Otto et al., 2016; Pimmler and Eppinger, 1994): First, existing product structures are broken down. Then, components are analyzed and revised. At this point, *Design-for-Variety* aspects (Martin and Ishii, 2002) can be integrated into the process. Subsequently, modules are formed based on different module-driving reasons.

Three fundamental methods in this area are notable. Pimmler and Eppinger use the *Design Structure Matrix* by Steward to represent the interaction of components in a product to subsequently form modules (Pimmler and Eppinger, 1994).

Components that have strong interactions are grouped into a module, rather than components that can be easily decoupled. Stone et al. use heuristics for module creation (Stone, 1997). These two approaches support the module creation from a technical-functional perspective. Ericsson and Erixon have developed the *Modular Function Deployment* method, in which modules are formed based on module drivers (Ericsson and Erixon, 1999). This method integrates product-strategic aspects into module creation. Numerous variations, further developments, and combinations of these methods exist in literature.

In some methods, the creation of modules is primarily cost driven. After analyzing a product family through its decomposition, Nepal et al. use so-called *cost drivers* to create modules using a mathematical model (Nepal et al., 2005). Schuh presents a high-level modularization strategy that references other methods and tools (Schuh and Riesener, 2017). After determining the target market and analyzing customer desires, the *VMEA methodology* is used for product concept development. This methodology, based on Caesar, enables a modular product strategy based on assembly sequences and costs (Caesar, 1991).

Some approaches in the literature on developing modular product families present not just a method but rather a framework for development. The *Platform Planning Framework* and the *Product Family Masterplan* are examples where cost aspects are also addressed (Harlou, 2006; Robertson and Ulrich, 1998). The *Platform Planning Framework* consists of three phases: *Product Plan*, *Differentiation Plan*, and *Commonality Plan*. The *Product Family Masterplan*, on the other hand, combines models for customer perspective, model engineering, and part view.

In addition to the presented methods for product generation development, there are also approaches in the literature from the field of systems engineering that support the development of system architectures based on the use of modular principles, especially during the conceptual phase of design. Bryant et al. support the concept creation and early evaluation through a computational matrix-based algorithm. The developed tool, which is based on this algorithm, is intended to assist engineers in generating design decisions and subsequent evaluations. The algorithm is founded on a functional basis and web-based design knowledge derived from historical lifecycle data of existing products (Bryant et al., 2005).

The SAMOA (System Architecture Model-based OptimizAtion) approach assists developers in the automatic creation of multiple design alternatives during the development process of complex system architectures to reduce the development times of different design alternatives. Based on the problem description, the system's functional architecture including the system interfaces, the collection of available components, and user-defined design rules, an automatic chaining of components based on the functional architecture is carried out. Through iterative optimization of the generated design alternatives, an automatically generated baseline of the system architecture is created, which can be further optimized by the developers (Albarello and Welcomme, 2012).

3 Challenges

The approaches introduced in Chapter 2.2 have shown that there are various methods to support the product generation development process for developing modular product families existing in the literature. On the other hand, several approaches for determining and evaluating costs, especially focusing on cost of complexity, were presented in Chapter 2.1. It is apparent that existing approaches for the specific determination and evaluation of variety-induced cost of complexity provide support following the actual product generation development process (see Figure 1). The consideration of cost of complexity during the *Design for Variety* and subsequent *Modularization* is not sufficiently supported. Instead, a final evaluation and subsequent selection of various product family concept alternatives, resulting from the product generation development, are based on determined cost of complexity savings from previously developed concepts (see Figure 1).

The subsequent evaluation of potential savings in cost of complexity does not support a complexity-cost-oriented product generation development. Moreover, high process costs in product development arise due to previously developed different concept alternatives (Figure 1). The goal, therefore, is to be able to consider the impact continuously and concurrently on the target size of cost of complexity during the individual steps of the product generation development.

To implement the concurrent consideration of cost of complexity, challenges have been identified, which will be elaborated upon further. The objectivity in recording the cost structure of the companies considered is of central importance, as it significantly influences the quality of the results of the subsequent complexity cost calculation and evaluation. Since the complexity cost calculation must rely on the cost values determined within the company, the accuracy of these cost values is crucial. Especially during restructuring measures, employees tend to make subjective statements about process times and costs, which distort the precision of the cost base and thus the complexity cost evaluation (Ripperda, 2019).

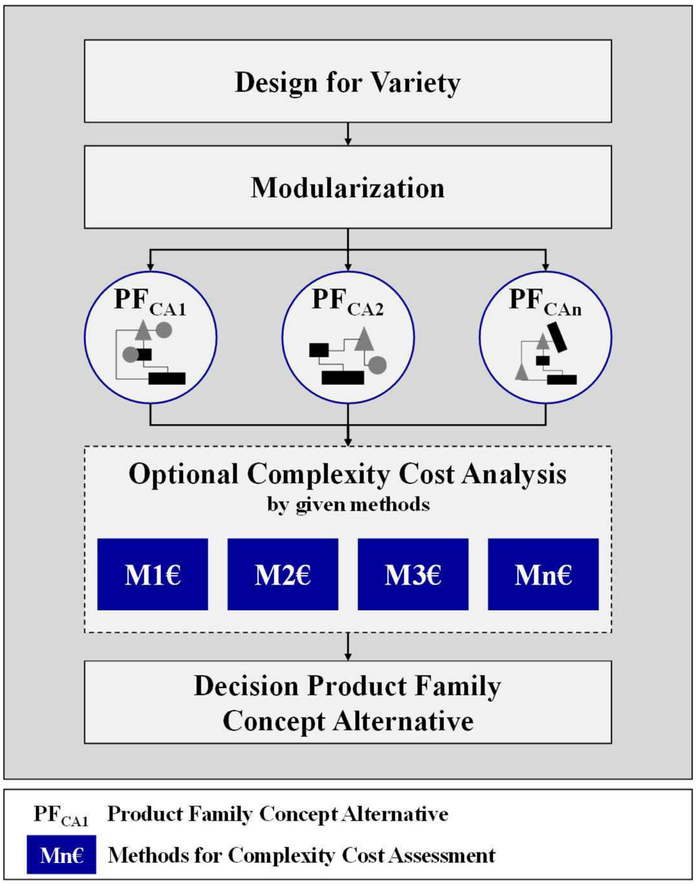

Figure 1. Current Consideration of cost of complexity in Product Generation Development (Ridder et al., 2023)

Furthermore, in addition to the individual components, the interactions and interfaces between them must also be considered. Sinha and Weck have shown that the structural complexity resulting from the interactions between product components has a fundamental impact on the complexity of a product family and thus on the variety-induced cost of complexity (Sinha and Weck, 2016). Reducing these interfaces must be supported alongside the standardization of the components.

The literature already contains a variety of proven methods (see Chapter 2.2) that support the development of modular product families. To enable a development-accompanying evaluation of cost of complexity, interfaces to the individual steps of the product generation development must be identified. The goal of these interfaces is the efficient use and integration of relevant cost values into the individual steps of the development process.

Finally, decision support must be enabled that allows the user to make complexity-cost-oriented decisions at the sub-concept level. Existing approaches only determine potential cost of complexity savings at the total concept level. The evaluation at the sub-concept level should enable the user to gain insights and impulses in the early phases of the product generation development that allow for targeted development to reduce emerging variety-induced cost of complexity.

The identified research gap and associated challenges lead to the research question:

How can variety-induced cost of complexity be considered continuously and integrated into the product generation development process?

To answer the posed research question, Chapter 4 will introduce a general framework for the continuous consideration of variety-induced cost of complexity.

4 Framework for the continuous decision-making concerning variety-induced cost of complexity

To continuously consider and thus strategically reduce variety-induced cost of complexity in product generation development, the following framework has been developed (see Figure 2). The goal is to assist the cost-oriented development of product generations by integrating approaches for analyzing variety-induced cost of complexity with methods of product generation development. This integration aims to avoid potentially arising process costs and thus development costs in a cost-efficient manner.

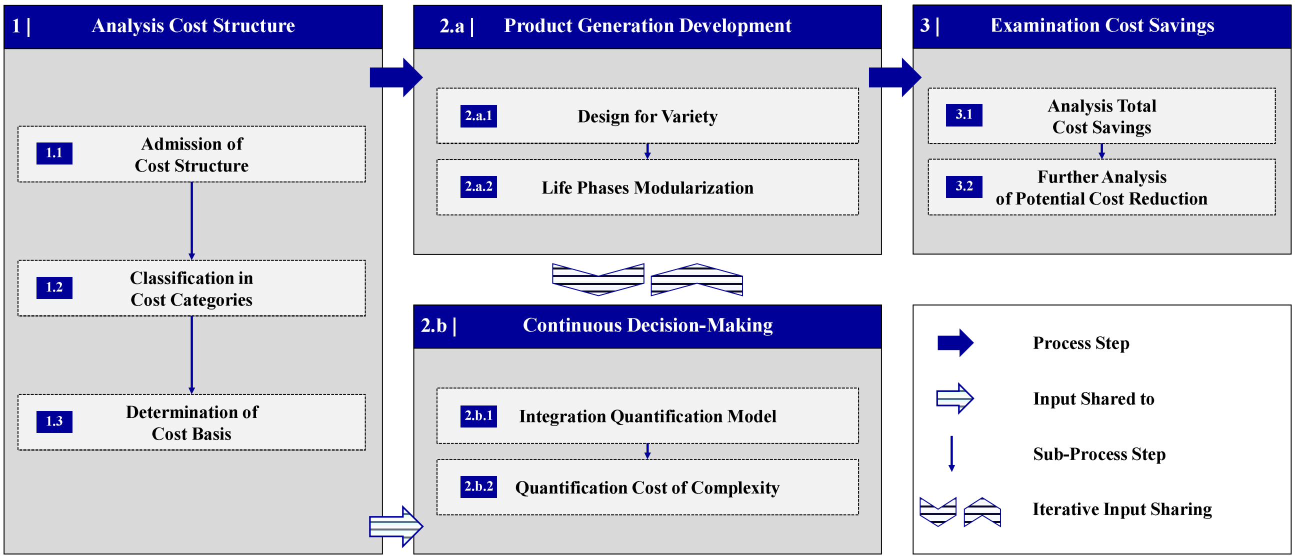

Figure 2. Framework for the continuous decision-making concerning variety-induced cost of complexity

The basis of the framework is the preliminary analysis of the company-specific cost structure. The included steps and sub-steps aim at an objective determination of the costs incurred within the company. Since the results from Step 1 are crucial for the quality of the results of the following sub-steps, the objective recording of the existing costs is of fundamental importance.

Step 2.a describes the necessary process steps of the product generation development. Here, particular attention is paid to *Design for Variety* and *Life Phases Modularization*. Within Step 2.a, proven methods and tools of the integrated PKT approach are used, which are assumed as the basis for the necessary consideration of the product generation development process (Krause and Gebhardt, 2023).

Moreover, the results from Step 1 form the basis for Step 2.b, which is the *Continuous Decision-Making*. This involves development-accompanying decision support concerning changes in variety-induced cost of complexity due to design changes within the product generation development (Step 2.a). The goal is the continuous impact analysis regarding the size of variety-induced cost of complexity.

Step 3 represents the examination of the total cost savings that could be achieved through the preceding steps and sub-steps. The goal is the total quantification of the potentially saved costs as well as the further analysis of potentials for cost reduction in the developed product family generation.

The following will elaborate on the individual steps of the framework shown in Figure 2.

4.1 Analysis Cost Structure

The basis of the framework is the analysis of the existing cost structure. In this context, the currently existing and known cost values of the company under consideration are analyzed and utilized. A time-based cost development of individual cost items is not considered in this context. The objective data collection of the company's costs is crucial for the subsequent data quality of the overall result. Since subjective statements and assumptions significantly influence the quality of the results, Step 1 is decoupled from the following sub-steps to allow an objective data collection. The aim is to analyze and built up a data base independently, to be used in the following steps of the framework.

The step *Analysis Cost Structure* consists of three sub-steps that support the recording of the company-specific cost base. Since companies have different cost structures, also in terms of their offered product model, the existing cost structure will be recorded in sub-step 1.1 to identify relevant cost types. The identified costs are then classified into defined cost categories in sub-step 1.2, life-phase-specifically, to allow for a later impact-appropriate cost analysis.

The determined costs are divided into three cost categories per product life phase: *material costs*, *process costs*, and *risk costs*. *Material costs* include the actual product material costs as well as necessary tool or storage costs, for example. *Process costs* mainly include personnel and manufacturing costs arising from necessary processes within all product life phases and consist, for example, of development, procurement or production costs. *Risk costs* describe potential costs that may arise from variant-appropriate product design, such as costs caused by the loss of suppliers if the number of suppliers has been significantly reduced during the variant-appropriate product design to achieve scale effects in material or component procurement.

The division into cost categories is necessary because changes at different points in the product generation development affect different cost classes. Finally, the company-specific cost base is determined, serving as input for sub-step 2.b. The result is semi-objective and processed cost values of the company considered.

4.2 Product Generation Development

Step 2.a describes the necessary sub-steps of product generation development for developing modular product families, that have a direct impact on reducing variety-induced cost of complexity. Here, the integrated PKT approach to develop modular product families and its sub-steps form the basis of step 2.a. The PKT approach has been successfully applied in several industrial projects and provides the necessary foundation for considering the development steps of modular product families (Krause and Gebhardt, 2023).

Step 2.a, *Product Generation Development*, consists of two sub-steps: *Design for Variety* and *Life Phases Modularization*. For both sub-steps, the integrated PKT approach offers proven tools for efficient support of the development of modular product families (Krause and Gebhardt, 2023). It is assumed that at the beginning of the product generation development, a status quo of a previous product generation is given and the external variance due to variant customer-relevant properties is known and predefined. Furthermore, it is assumed that the customer-relevant properties and requirements for the product itself do not change within one product generation.

For sub-step 2.a.1, *Design for Variety*, the 3-Level Variety Allocation Model (VAM) is used, which allows the allocation of customer-relevant *Variant Differentiating Properties* in terms of their implementation through *Variant Components* (Gebhardt et al., 2012; Kuhl et al., 2021). This involves mapping specific product properties, which can be selected by customers on the market side, to the implemented *Variant Components* and their internal diversity. Through the further development of the VAM and its extension to include the target size of cost of complexity, impacts on variety-induced cost of complexity can already be analyzed and considered at the sub-concept level, during variant-appropriate product design.

Here, costs are assigned to individual levels of the 3-level VAM (see Figure 3). For example, categorized *process costs* are integrated and considered at the level of *Variant Product Characteristics*. *Material costs*, on the other hand, are integrated at the level of *Variant Components* and analyzed concerning the reduction of cost of complexity. Furthermore, relevant information from the *Variant Product Characteristics* and *Variant Components*, which influence variety-induced cost of complexity, is connected to step 2.b by an interface. This primarily involves process times, personnel efforts or the number of variants per component. The goal is to particularly identify variant components and consider them in the complexity cost evaluation, which have a significant influence on the total cost structure. The focus on these components is intended to bring the resulting effort of complexity cost calculation and evaluation to a sensible level for efficient application.

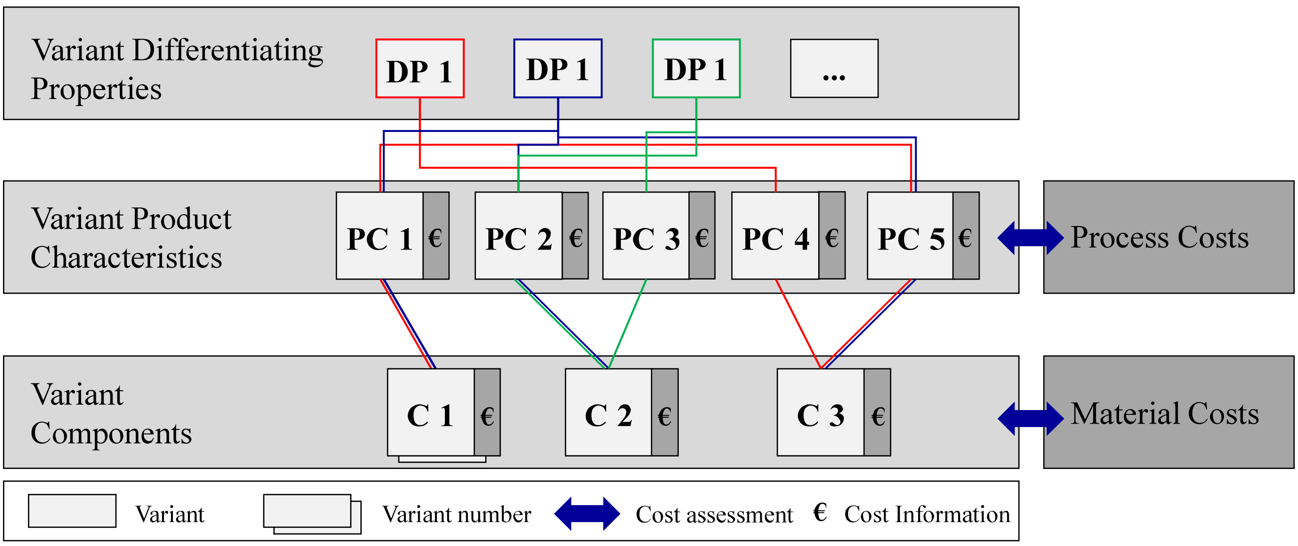

Figure 3. 3-level Variety Allocation Model (VAM) - Cost Integration

In step 2.a.2, the previously developed variant-appropriate product structure is divided into technical-functional and product-strategic modules in the *Life Phases Modularization*. The life-phase-specific module structures are then harmonized over the entire product lifecycle. For this purpose, the *Module Process Chart* (MPC) from the integrated PKT approach is used as the basis (Krause and Gebhardt, 2023). By integrating cost of complexity as a consideration in the MPC, variety-induced cost of complexity that result from product-strategic decisions are taken into account. The goal is to enable the user to consider these during the module harmonization process in the MPC. The formation of different module structures affects the resulting cross-life-phase cost of complexity and should be made visible to the user.

A key challenge are the iterative calculation and evaluation steps between step 2.a and 2.b. The interfaces between the tools used, VAM and MPC from the integrated PKT approach (Krause and Gebhardt, 2023), and the quantification of the resulting impact of cost of complexity are of crucial importance. Specific attention is paid to efficient data integration and preparation to minimize the process costs arising from continuous evaluation.

4.3 Continuous Decision-Making

The core element of the development-accompanying consideration of variety-induced cost of complexity is represented by step 2.b, *Continuous Decision-Making*. The goal of step 2.b is the iterative and development-accompanying quantification of potentially emerging variety-induced cost of complexity resulting from constructive measures in sub-steps 2.a.1 and 2.a.2.

For this purpose, the company-specific cost base created in sub-step 1.3 is integrated into a generic *Quantification Model*, which forms the interface to sub-steps 2.a.1 *Design for Variety* and 2.a.2 *Life Phase Modularization*. The Q*uantification Model* allows the integration of the created cost base into the product generation development process through defined interfaces to the sub-steps from Phase 2.a. As already presented in Chapter 4.2, proven methods from the product generation development of the integrated PKT approach are utilized and expanded with generic cost interfaces here to implement different cost structures coming from different companies considered.

Based on the *Quantification Model*, sub-step 2.b.2 quantifies the effects of design decisions from 2.a on the variety-induced cost of complexity in an iterative process. The aim here is to provide the user with efficient and direct decision support to make targeted decisions regarding the reduction of variety-induced cost of complexity.

4.4 Examination Cost Savings

In step 3, *Examination of Cost Savings*, the total costs including the potentially saved variety-induced cost of complexity are determined and analyzed in sub-step 3.1. This is intended to finally validate the total concept created in step 2.a. By establishing the *Total Cost Savings*, the developed total concept can be endorsed, also in terms of acceptance within the company.

Furthermore, based on the determined costs, an updated cost base can be created. Based on this updated cost base and the newly developed product family generation, further analyses regarding cost-saving potentials are initiated in the final sub-step 3.2, to identify emerging cost potentials during the current product family generation.

5 Discussion and outlook

In this research, a framework has been presented that outlines the necessary steps and sub-steps for a continuous and development-accompanying consideration of variety-induced cost of complexity during product generation development and links them. For this purpose, potential design decisions during the product generation development process are iteratively evaluated, providing the user with direct decision support. This is intended to enable cost-oriented development, particularly at the sub-concept level.

The basis for this is the objective recording of the existing cost structure in the company being considered. Since the cost base forms the calculation basis for quantifying cost of complexity, the data quality of the recorded cost base significantly influences the quality and significance of the developed product family generation regarding saved cost of complexity. The data quality is primarily determined here by the objectivity of data collection. While material costs, for example, can be objectively determined through past orders regarding raw material and purchase prices, the process costs to be used here typically rely on process times obtained through various expert surveys. The subjectivity integrated into the database as a result should be as fully minimized as possible and should be further addressed in subsequent research.

Due to the increasing relevance of service-oriented business models among manufacturing companies, the transfer of the determined cost basis into a generic cost quantification model is of high importance. With a higher degree of integrated services from products to holistic product-service systems offered in the market, the application of the presented framework must be possible on various cost structures. As the increasing integration of services can also positively influence the internal variety within companies, this also affects the resulting variety-induced cost of complexity coming from service-oriented business models and product-service systems implemented (Rennpferdt et al., 2023). The conversion of the determined company-specific cost basis into a universally applicable quantification model within the presented framework ensures this consideration. However, particularly with product-service systems, there is the challenge that companies often do not know the needed costs related to the development of the required infrastructure during the service life phase. The lack of knowledge about specific cost values within the companies under consideration, even within traditional business models, raises the question of the required level of detail for the cost structure to be recorded. The development of an efficient cost-benefit ratio is currently part of parallel research.

In addition to physical components, future research should also focus on the consideration and integration of software components of the product architecture and their impact on variety-induced cost of complexity. Especially due to digitalization and the increasing relevance of product-service systems, software components are becoming more significant in their proportion of the product architecture and relevance. In this context, future research must also take into account relevant approaches from systems engineering regarding the continuous consideration of variety-induced cost of complexity and relate them to the framework presented in this research.

Regarding a comprehensive consideration and inclusion of all relevant design and cost data, future research should also focus on software-based support of the approach. Due to the multitude of cost data to be integrated in conjunction with the necessary design data, a purely manual consideration of the data can only be implemented effectively with software support. The fundamental and overarching goal is to provide the user with efficient decision support. The manual effort of cost-based quantification should be minimized in this regard.

The framework presented in this research for the continuous consideration of variety-induced cost of complexity must be tested and validated in future research projects using industrial examples, considering real influencing factors.

6 Summary

A continuous and development-accompanying consideration and evaluation of variety-induced cost of complexity during product generation development can target their reduction effectively. Therefore, the goal of this research is to demonstrate the need of the development-accompanying consideration of variety-induced cost of complexity and to present a framework that enables their continuous consideration. In Chapter 2, approaches were presented that support the development of modular product families within product generation development, as well as methods focused on concept cost evaluation within product development. Building on this, Chapter 3 demonstrated that existing approaches do not allow for a development-accompanying and continuous evaluation of cost of complexity in product generation development. Furthermore, challenges have been addressed that must be considered when integrating a continuous consideration of cost of complexity. Based on these challenges and the research question formulated in Chapter 3, in Chapter 4 a framework for the continuous consideration of variety-induced cost of complexity was presented, setting out the necessary steps and sub-steps in relation to each other.

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