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Knowledge-Based Decision Support for Concept Evaluation Using the Extended Impact Model of Modular Product Families

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Featured Application: The developed method for knowledge-based decision support is mainly aimed at companies that have to deal with a high number of variants in their product portfolio and decide to develop modular product architectures to manage the internal variety.

Abstract: The design of modular product families enables a high external variety of products by a low internal variety of components and processes. This variety optimization leads to large economic savings along the entire value chain. However, when designing and selecting suitable modular product architecture concepts, often only direct costs are considered, and indirect costs as well as cross-cost center benefits are neglected. A lack of knowledge about the full savings potential often results in the selection of inferior solutions. Since available approaches do not adequately address this problem, this paper provides a new methodological support tool that ensures consideration of the full savings potentials in the evaluation of modular product architecture concepts. For this purpose, the visual knowledge base of the Impact Model of Modular Product Families (IMF) is used, extended and implemented in a model-based environment using SysML. The newly developed Sys-IMF is then applied to the product family example of electric medium-voltage motors. The support tool is dynamic, expandable and filterable and embedded in a methodical procedure for knowledge-based decision support. Sys-IMF supports decision makers in the early phase of interdisciplinary product development and enables the selection of the most suitable modular solution for the company.

Keywords: product architecture; modularity; data management; MBSE; SysML; KPIs; decision support; product concept evaluation; knowledge management

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1. Introduction

Over the last decades, manufacturing companies are exposed to various challenges as a result of current trends such as globalization and the individualization of customer requirements. As a consequence, markets with rising cost pressure and competitive characteristics have emerged. Companies are required to increasingly diversify their portfolio of goods and services in order to maintain a competitive edge in the industry over time. Concurrently, the growing external product diversity must be internally managed, or else it would increase effort and thereby increase variety-induced costs across the departments of a company [1].

From a product development perspective, the use of modular product families is a suitable strategy that can be pursued to control internal variety [2–4]. By specifically influencing modularity, the externally required diversity of offers can be addressed while simultaneously reducing the internal variety and thus costs [3]. Suitable methods of modularization have become established over the years and are successfully used in industrial practices [4]. However, there is still a need for action in the objective evaluation and selection of suitable modular product architectures [5,6]. Here, the companies mostly only use the expected manufacturing costs, which include material and production costs, as the only decisive criterion [7]. Modular product architectures, however, often lead to standardized, oversized components across the entire product family, which can result in rising manufacturing costs, but at the same time generates many indirect benefits (e.g., reduced development, administration or logistics expenses; shortened time-to-market or increased portfolio flexibility) along the entire value chain [8]. These indirect savings are not usually focused on by traditional evaluation methods when selecting suitable modular product concepts, as they are both difficult to identify and quantify. As a result, companies often do not opt for the most economical alternative and leave out essential benefits [5].

Using the Impact Model of Modular Product Families (IMF), a qualitative knowledge base has been developed over the years that systematically visualizes the economic savings potentials of modularity in relation to the different target variables and life cycle phases and traces them back to the properties of modularity [9,10]. The model was initialized based on a comprehensive literature review and validated using several empirical case studies [11]. However, statements about the effects of modularity are currently only available in qualitative terms (e.g., logistics costs decrease; time-to-market is shortened), which is not sufficient in the context of a decision situation for selecting alternative product architecture concepts. In addition, the IMF contains large amounts of data with many dependencies, which are not manageable at this stage and need to be systematized and mapped consistently for application.

The objective of this paper is to extend the qualitative IMF with quantitative calculation bases and thus to develop a knowledge-based decision support system that can be used for the quantitative evaluation of alternative modular product architecture concepts. In order to be able to consistently and dynamically map and extend the large amount of information and complex dependencies in the IMF, we model the IMF using SysML and make it usable for decision making. For this purpose, the Section 2 outlines the relevant basics with respect to the IMF, the existing evaluation methods in the context of modular product architectures and the basics of SysML as a knowledge management tool. Building on the derived research demand in Section 3, we implement the full model with all essential attributes in SysML using Cameo Systems Modeler and assign appropriate KPIs to the effect chains in IMF in Section 4. The fully described model serves as knowledge base for the newly developed approach for the case-specific evaluation of alternative modular product architecture concepts. This new method is presented in Section 5 and then applied and validated using an industrial application example of electric medium-voltage motors. Finally, the results are discussed (Section 6), and further research needs are identified (Section 7).

2. Literature

2.1. Economic Impacts of Modularity on a Firm's Objectives

The aim in designing modular product architectures is to influence the modularity of a product architecture in such a way that this results in functional and/or product strategy advantages throughout the company [4]. The intent is not necessarily to increase modularity, but to design a product architecture that is adapted to company-specific boundary conditions and focusses on the benefits of all lifecycle phases. In this context, the term product architecture can be defined as the totality of the functional and physical descriptions of a product [12]. This includes not only the arrangement of the functional elements, but also the definition of the specification of the interfaces between the physical components as well as the assignment of functional elements to the physical components. The modularity of a product architecture is understood as a gradual property that can be described by the equally gradual characteristics of decoupling, commonality, combinability, interface standardization and function binding [13]. Through commonality, modules are used in different products to enable savings through economies of scale. By combining the modules, different product variants can be configured. An essential measure for realization is interface standardization and function binding. For the latter, the modules fulfill exactly one function or a defined set of functions [13]. Hackl et al. added the attribute of oversizing and contextualize the characteristics [9]. As such, commonality and combinability are defined as the key levers for achieving economic objectives, and the other characteristics are understood as measures for achieving these goals [9,11].

Various economic effects can be achieved along the entire product life cycle through the different expressions of modularity. The knowledge of these advantages is of great interest and should be considered when deciding for or against a modular product structure alternative [11]. However, the effects are mostly indirect, difficult to quantify and go far beyond pure cost considerations [14]. A comprehensive tool for systematically capturing the effects of modularity on business targets is provided by the Impact Model of Modular Product Families (IMF) [8–11]. In the model, which has been validated several times, the drivers and effects of modularization are visualized; the causal relationships are recorded, and the effects are assigned to the individual product life phases of a company. Furthermore, the effects are related to the economic targets of time, costs, quality and flexibility, which can be positively or negatively influenced depending on the degree of modularity. Figure 1 shows an excerpt of the static IMF with an exemplary chain of effects from the procurement phase. The complete model with the more than 70 impact chains can be found in [10].

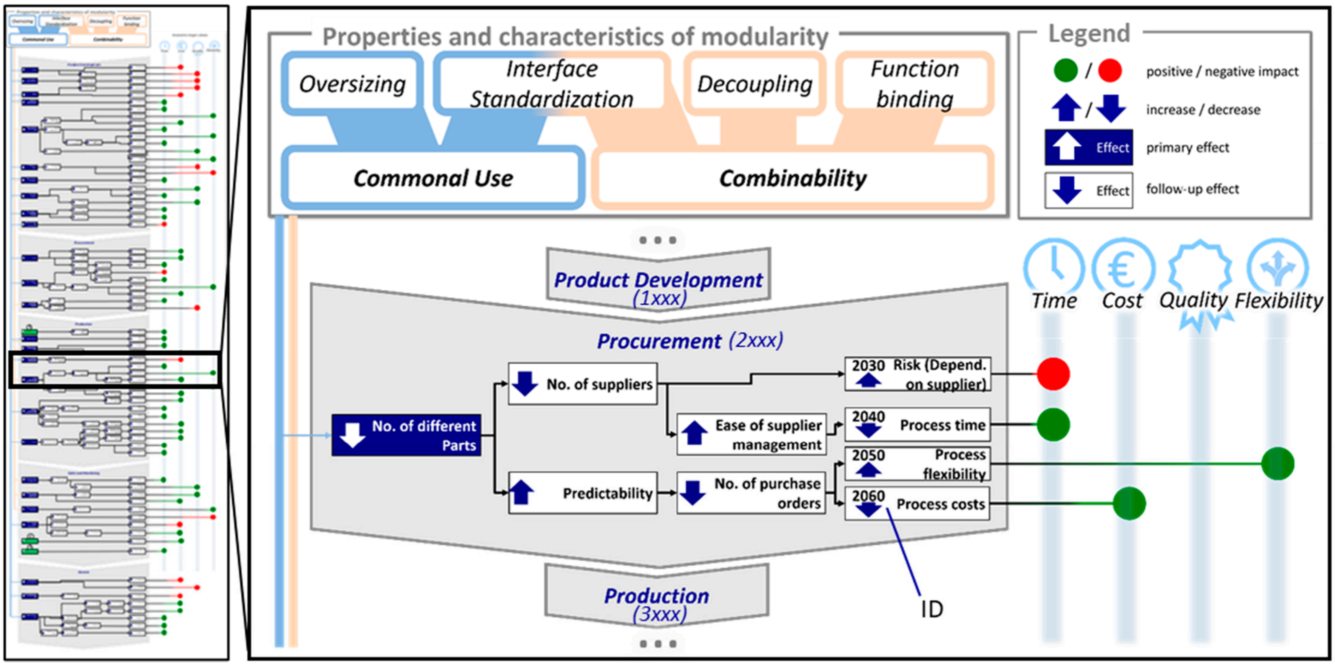

Figure 1. Visual-based static Impact Model of Modular Product Families (IMF) [10].

In the IMF excerpt for the life phase of procurement, it can be seen that the characteristic of communal use (blue) has an impact on the primary effect of the number of different parts. This results in further follow-up effects in the illustrated impact chain. The initial effects that result directly from the properties of modularity are termed primary effects [9]. The reduced number of different parts means that fewer orders need to be generated, and the orders that are initiated include larger quantities. Unit costs can thus be reduced by larger quantities due to volume discounts. The consequential effects explain the resulting causal relationships in more detail and end in an economic outcome. This can be both product-related and process-related. In the example shown in the excerpt, the ordering processes are simplified so that the impact chain presented has more of a process reference and potential savings are achieved there. The last effect of a chain is always declared with an ID number in order to be able to assign the respective effects more easily to the influenced economic target values [10].

A significant advantage of the IMF is the consideration of different life cycle phases and the traceability to product structure-related causes as well as the consideration of company-, project- and product-related boundary conditions [8]. The model currently contains more than 70 effects, which have been validated in several empirical case studies and examined for their temporal dependency as well as for the influence of different boundary conditions (e.g., quantity, market position, strategy). Thus, a huge amount of data is available, which is no longer manageable for the application in the industrial context and is currently only systematized rudimentarily [15]. Moreover, the impacts on the economic targets are only available in qualitative form (increase, decrease), which is not sufficient for a targeted comparison of alternative modular product architecture concepts.

2.2. Existing Approaches for Decision Support in Modular Product Family Design

The overall goal of this paper is to support the decision-making process in the evaluation and selection of modular product architecture concepts. The existing methods in this field can be classified into the four categories of structural indices, costing methods, universal methods and comprehensive methodologies (see Figure 2) [16]. For each category, the main methods are briefly presented below, and their suitability in the context of the objective is reviewed.

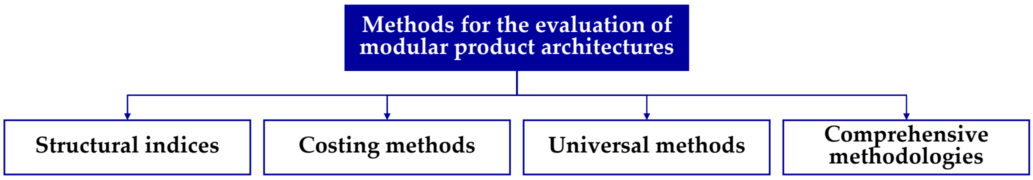

Figure 2. Categorization of methods for the evaluation of modular product architecture concepts according to [16].

Most of the structural index methods focus on a descriptive measurement of the commonality of product architectures. The authors introduce models for evaluating the commonality of product architectures, considering common components (Degree of Commonality Index (DCI) [17]; Total Constant Commonality Index (TCCI) [18]), commonality and performance optimization [19], process commonality [20] or platform commonality [21]. The approach of Sanaei et al. for evaluating modularity tradeoffs optimizes product architectures through cluster cost, number of modules and size diversity [22]. The focus on trade-offs allows a comparison of alternatives, although the authors consider only a small subset of the relevant KPIs. Baylis et al. use a Pareto optimization to include other qualitative strategic objectives in the decision-making process, especially for platform development [23].

On a more business level, costing methods are used that focus to a greater extent on the economic success of product modularity. In many approaches, proprietary monetary performance parameters are developed for measuring modular product architectures. As comprehensive as it is fundamental, Meyer and Lehnerd's work contains strong aspects of strategic planning for product platforms and provides an indication of what to consider when evaluating them [24]. However, specific guidance for modularization selection problems is not provided. Based on these findings, Abdelkafi [25] and Blecker and Abdelkafi [26] developed a key performance indicator system to evaluate individual product families. The authors' approach, however, focuses mainly on improving lead time. The method postulated by Fixson, instead, proposes relevant factors and allocation rules for a cost evaluation of product architectures [27,28]. The approach takes into account both architectural aspects and costs from different life cycle phases. However, the approach operates at a general level and lacks an operational description of KPIs and structural features. Furthermore, many of the approaches focus on individual life phases and on specific indicators. Despite their scope, these methods lack flexible applicability to company-specific problems [16]. The determination of the costs incurred by summing up individual process steps by means of activity-based costing (ABC) enables a flexible and sufficiently precise determination of the process steps and their monetary evaluation [29]. The aim of these methods is an exact calculation of costs incurred on the basis of the required activities and processes, whereby the expenses incurred in indirect company areas are allocated to individual cost units. This enables costs to be allocated transparently and in line with their origin, and indirect costs are no longer allocated on a flat-rate basis via overhead costs [29]. Essential approaches in the context of modular product architectures are [5,30,31]. The methods that assign process costs to modularity levels, such as [32], are severely limited in their practicality because of the high degree of imprecision involved in determining the input variables. The informative value of the resulting costs is therefore unacceptably high. In other approaches, such as the approach to variant costing [33], costs are extrapolated. In addition to the fact that the overall effort required for the method to be applied is relatively high, the costs determined in this way are also not sufficiently accurate and thus not suitable for practical decisions.

The universal methods for evaluating modular product architecture concepts are based on a joint consideration of technical as well as product strategy aspects. Robertson and Ulrich's method is based on a trade-off model that considers conflicts between a structural indicator and a product strategy indicator [34]. The Platform Evaluation Concept Scorecard according to [35] summarizes several evaluation metrics that are decisive for the subsequent evaluation and lists them in a tabular form. Based on this, a universal set of metrics is proposed for multi-criteria concept evaluation with respect to different life phases [36]. However, the authors' evaluation is based purely on point scoring and tabular representations. Without visual representation, it is therefore difficult to identify the relevant indicators in the large number of key metrics. Similar to [37], there is no link to the company's key performance indicator system. The usage of the Balanced Scorecard as developed by [37], however, has a stronger focus on product strategic factors. The concept uses elements of multi-criteria evaluation and has a partially visual approach. Similar to other scorecards, the focus is on controlling strategic goals rather than operational or tactical decision making. In addition, product structural aspects are covered by KPIs but are not visually supported or selected on a case-specific basis.

The last group of evaluation approaches includes comprehensive methodologies. These are holistic approaches consisting of multiple, assessment-related methods, including processes or steps for planning, developing, evaluating and controlling product families in general. Key approaches in the field include [4,38–42]. The authors focus on different parameters in the context of product design, but do not include comprehensive economic targets in the decision-making process. In addition, the company-specific and thus decision problem-specific adaptation is hardly given.

Based on the analysis and findings, there is a lack of an integrated concept evaluation approach that considers the key case-specific impacts of modular product architectures on a company's economic targets. This gap will be addressed in this paper by extending the IMF as the fundamental knowledge base for decision support.

2.3. Consistent Data Modeling Using MBSE

Due to the large amount of data and many dependencies in IMF, the static model should be made usable for decision making with the help of systems engineering. Systems engineering encompasses the overall development and control of complex systems. Based on requirements, a system architecture is created from which the system behavior can be derived [43]. Model-based Systems Engineering (MBSE) includes processes and methods as well as system modeling, system requirements, design, analysis, verification and validation. A part of MBSE is the modeling of systems with all associated information. By connecting different data in one system, MBSE enables, based on a joint database, easier knowledge and document management. In most cases, network models are created [44–46]. In recent years, the MBSE approach has become increasingly important in terms of system modeling, as this approach allows the creation of more complex, interdisciplinary models [47]. This involves modeling the system elements and the information links within a system. The modeling language SysML is based on the Unified Modeling Language (UML) [45,48]. The Cameo Systems Modeler (Cameo) by No Magic is an industry- and platform-leading environment that provides the most standards-compliant SysML tools and diagrams [49]. Cameo can be used to create relevant diagrams in the context of the objective, with a focus on SysML diagrams [50]. The diagrams allow the user different views on the model. From initial analysis and feasibility studies of implementing the IMF using Cameo, block definition diagrams (BDD) in particular have emerged, as many different types of elements need to be linked together [15]. The various elements are implemented as blocks, since blocks are the system elements that are most flexible in interacting with other system elements and depositing additional attributes. The IMF is currently only incompletely implemented and not suitable for use in evaluating modular concepts. Here the consideration of further requirements is necessary, which are analyzed in the context of the method design and addressed by extensions and adaptions to the model.

3. Materials and Methods

In order to achieve the aforementioned goals of this work and to develop a methodical decision support, the research procedure of the Design Research Methodology (DRM) according to Blessing and Chakrabarti is applied [51]. Over the years, this approach has established itself as an essential procedure for developing product development methods and tools. The first step is to clarify the research objectives and analyze the existing situation. The central objective of this paper is to answer the following overarching research question in a theoretically well-founded manner and oriented towards the requirements of real decision-making situations:

How can the impact model of modular product families (IMF) be extended and made usable for the concept decision in the evaluation and selection of modular product architectures?

To answer the research question, applying the DRM in descriptive study I, we first sharpen the understanding of the problem. This is done by interviewing several experts with a total of more than 40 years of experience in consulting and implementing modularization projects in relation to the IMF and their capabilities as decision support. The requirements derived from this will be used in the subsequent prescriptive study to develop the solutions to the given problem. For this purpose, the IMF is adapted to the identified requirements, and a methodical procedure for supporting decision-making situations is developed. For this purpose, the IMF is modeled using SysML. The development of the newly generated Sys-IMF within the prescriptive study is based on the methodological approach for modeling data according to [15]. Here, the initial model with the model elements and the connection types is first analyzed, and a data model is created as an extensible metamodel. Subsequently, implementation definitions are derived in the SysML model language with adaptations for the different elements, and the IMF is fully implemented with all data. Finally, the Sys-IMF is integrated into a methodical procedure for decision support in the evaluation of modular product architectures within the scope of the synthesis and finally applied and evaluated on the basis of an industrial project example (descriptive study II).

4. Results

The following section presents the results obtained using the methodological approach introduced in the previous section. For this purpose, the identified requirements for the decision support to be developed are first introduced, and then the modeling of the Sys-IMF in Cameo is described. Thereby not only the extensions in the form of boundary conditions, KPIs and temporal information are presented, but also the interface for the maintenance and feeding of the model is described.

4.1. Requirements for the Knowledge-Based Decision Support

Based on the interview study with the consulting experts for modularization projects, a total of six essential requirements are derived for the decision support to be developed based on the IMF as a knowledge base on the effects of modular product architectures (see Table 1).

Table 1. Requirement's overview.

#	Requirements	Model Part	Type of Implementation
R1	Consisting storing of data in one source	all elements of IMF	SysML
R2	Providing KPIs for quantitative evaluation	economic target values, KPIs	SysML
R3	Providing time dependence of impacts	economic target values, time dependency	SysML
R4	Providing a two-ways flow of the model (Import/Export)	all elements of IMF	SysML, spreadsheets
R5	Filtering impacts without programming	all elements of IMF	Spreadsheets
R6	Selecting economic factors depending on specific boundary conditions	economic target values, boundary conditions	Spreadsheets

The possibility of consistent data modeling in a single source of truth is essential for a targeted evaluation and selection of modular product architecture concepts (R1). This has been confirmed in past studies [15] and stems from the fact that the IMF contains over 70 impact chains and needs to be constantly adapted and extended. As mentioned before, the implementation is conducted by means of SysML (*Cameo Systems Modeler*, Version 19.0, NoMagic Inc., 700 Central Expy S Ste 110, Allen, TX, USA) in the Cameo Systems Modeler. Of additional great importance is the provision of KPIs in the model to allow a quantitative comparison of alternative product architecture concepts (R2). This is currently not yet possible and will be implemented in the following iterations. For this purpose, new or existing quantification measures are developed for the various economic targets and stored in the model. The same applies to the time dependence of the effects (R3). These have already been included in an extensive empirical study [11] and will be deposited in the knowledge base. The provision of an import/export interface (R4) aims at two different aspects. On the one hand, this should enable transfer to a common and intuitive data management environment using spreadsheets. The Cameo Systems Modeler is not suitable here, so an interface to MS Excel is to be developed to enable filtering (R5) as well as the selection of effects based on certain company-specific boundary conditions (R6). On the other hand, the two-ways-flow (R4) should also create a path to add more data to the IMF. This is tremendously important because the validity of the knowledge base increases with the amount of data on empirically determined effects of modularization. The import/export function thus enables the easy maintenance and simple addition of further data via MS Excel import. In the following, the support requirements are implemented according to the presented research approach.

4.2. Data Model and Block Definition Diagram of the IMF

The basis for modeling the IMF in SysML is provided by a data model. Thereby not only the single data elements are important, but also the relations between the elements. Based on [15], the data model for the extended IMF is initialized with respect to the established requirements from the previous subsection (see Figure 3).

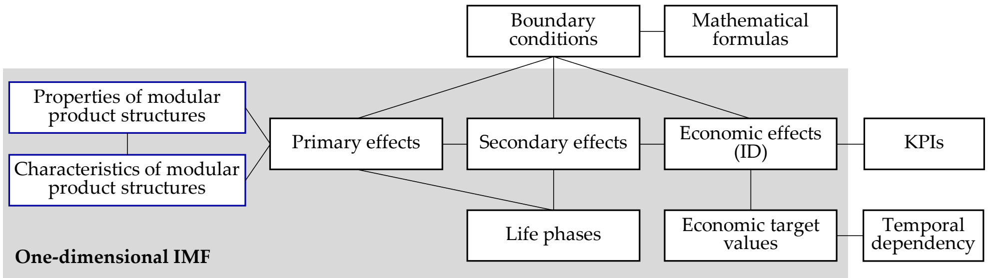

Figure 3. Extended data model of the IMF for the implementation in SysML.

All system elements that are linked in this model must also be connectable in the SysML-model. The gray outline indicates the one-dimensional IMF as represented in the current static visualization. The boundary conditions are coupled to all effect classes and can be described by mathematical formulas. First approaches for this can be found in [15]. The KPIs are assigned solely to the economic effects that are directly related to the economic target values. This enables a targeted quantitative determination of the essential parameters for the subsequent comparison of modular product architecture alternatives. The time dependency is directly related to the economic target values in order to enable a direct indication of the time-related occurrence of an effect.

The data model is implemented in accordance with the chosen methodological approach using block definition diagrams (BBD), which enable interaction with other system elements and the storage of additional attributes [15]. Figure 4 shows a segment of the implemented IMF with Cameo Systems Modeler for the life cycle phase of procurement.

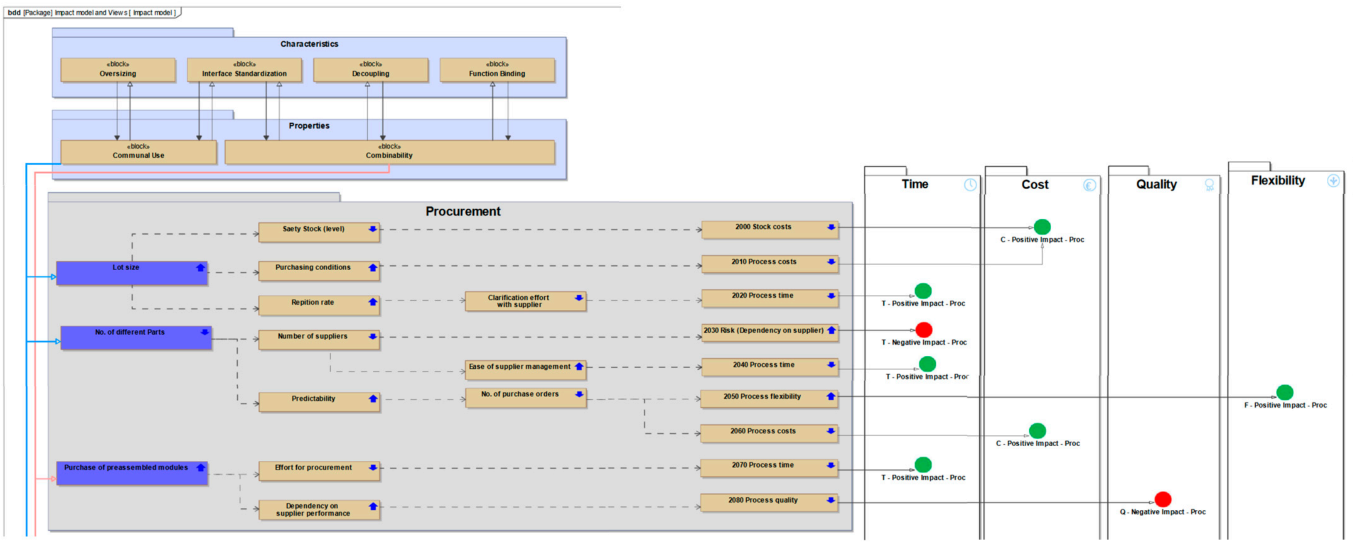

Figure 4. Extract of the block definition diagram of the IMF in Cameo Systems Modeler (Sys-IMF) for the life phase of procurement.

The visualization in the Sys-IMF is strongly based on the representation of the static IMF, even though Cameo is not primarily a visualization tool, but rather a consistent data management system. As in the initial model, the properties of modularity lead to effects in the individual life phases, which in turn influence the economic target values of a company. Each element in the Sys-IMF is defined here by a system element block. By double-clicking, further information about the respective element can be retrieved, such as the type of boundary condition and its relationship, the KPIs or the time dependency. The implementation of these system elements is presented in the next subsection.

4.3. Integration of Boundary Conditions, KPIs and Temporal Dependency

The consideration of boundary conditions is enormously important for decision support, since these have a significant influence on the expression of economic effects [10,11,15]. Company-specific aspects (e.g., industry, strategy, market position, value chain), product-specific aspects (e.g., product life cycle, quantity, complexity) or project-specific aspects (e.g., project volume, project duration, qualification of employees) can have a major impact on the achievable targets. This information must be stored for the effects in the Sys-IMF in order to be able to derive particular patterns for the different boundary conditions in the long term.

In order to consistently represent this feature in the model, the different boundary conditions are linked to the effects and modeled by means of a dependency matrix. This matrix is used to clearly display cross-diagram relationships and dependencies between a wide variety of model elements. The model range to be displayed in rows and columns can be adjusted manually and, in addition to visualizing relationships between model elements, new relationships can also be generated. Consequently, the matrix allows complex interrelationships to be clearly presented and thus better analyzed [52].

Figure 5 shows an example of such a dependency matrix for the procurement phase and selected boundary conditions. The matrix shows the strength or weakness of an effect in the context of a particular boundary condition. This also represents the first step towards linking mathematical formulas, which has already been implemented to some extent in [15].

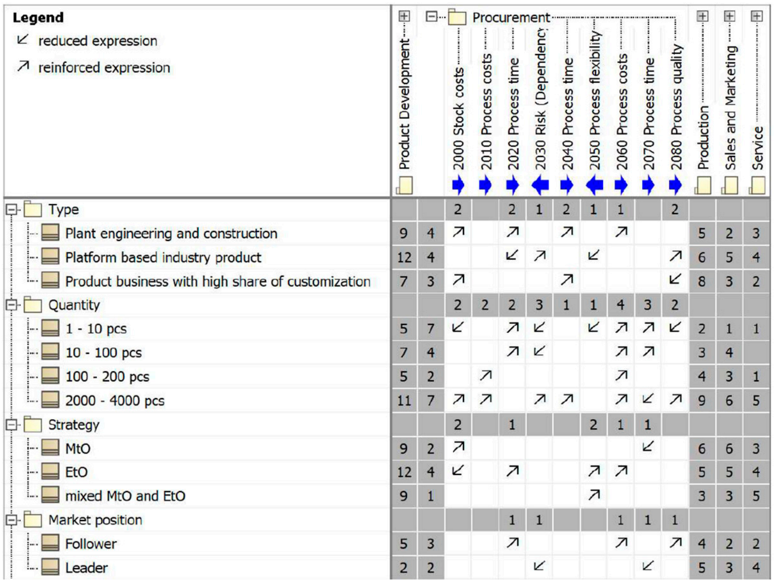

Figure 5. Dependency matrix representation of boundary conditions for economic effects.

The rows contain examples of company-specific boundary conditions, which can be adapted or extended as required. The columns include the target variables with IDs that essentially represent the respective impact chain. The correlation indicates the direction of the characteristic—for example, in the case of process costs (ID 2010), significant savings can only be achieved from a quantity of around 100 units. Such relationships are easily represented to the Dependency Matrix and can be modeled consistently. By using relation maps, the relationships from the matrix can be visualized and important statements regarding the occurrence of the respective effects under certain boundary conditions can be obtained [53]. Figure 6 shows an example of a partial relation map for the number of pieces (1–10 pcs).

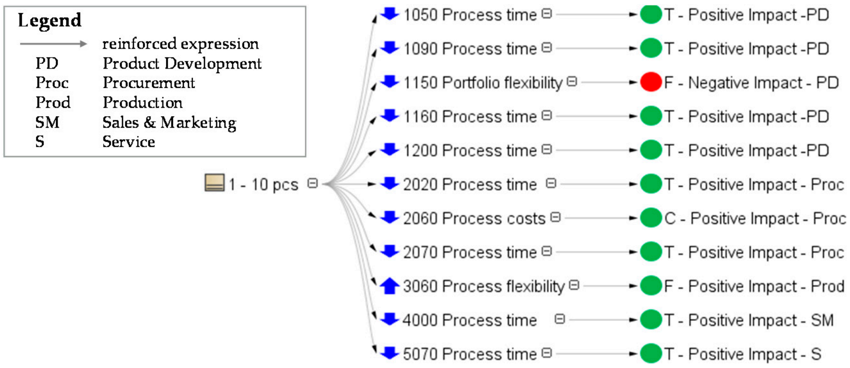

Figure 6. Partial relation map on the example of the boundary condition of the number of pieces.

In the figure, the connections for the reinforced expression are shown, but other dependencies or boundary conditions can also be displayed. The relation map thus allows a targeted analysis of the economic impacts in relation to the stored boundary conditions for the respective life cycle phase and can be edited directly in the representation.

The KPIs are integrated at the level of economic effects (see Figure 3) in order to enable direct allocation to the key target values for the subsequent concept evaluation. For this purpose, suitable KPIs with associated calculation bases are assigned for each impact chain (Table 2). These arise partly from the literature as well as from the analysis of the individual impact chains per se. Since the model includes different target variables such as costs, time, quality and flexibility, different parameters in the form of KPIs are required. For the cost-related effects, the indirect cost savings through the savings of process costs are often determined. Here the calculation principles are frequently based on the methodical procedure of the Time-driven Activity-based Costing method (TD-ABC) [54], with which the costs are calculated by the necessary process times and the number of repetitions as well as the respective cost rate of the process step, e.g., the order costs (ID 2060) in the procurement phase. However, direct cost calculation methods are also stored in the model, such as the calculation of direct material costs (ID 1000 and 1040) according to [55]. Some costs are difficult to quantify in the early stages of product development and can only be estimated in relation. These often result indirectly from the previous primary effects and allow extrapolation to the respective economic target values. This is, for example, the case with the reduced process costs in production (ID 3090), which results from the parallelization of production processes and the resulting improved balance of machine utilization. Here, the calculation of the saved costs would involve a very high effort and would be subject to high uncertainties, since many imprecise estimations have to be made. The Machine Utilization Ratio is used here as an indirect indicator, which provides a tendency direction of the target value in relation to the comparative evaluation of concept alternatives.

To determine the target value of time, the process times resulting from the saved variety-induced complexity are primarily determined as KPIs. In this case, effects often occur which lead to a shortening of process steps and thus to reduced throughput times or time-to-market. These savings potentials can often be determined using the critical path method of a process chain (e.g., ID 1080 or ID 1110 in the product development phase) [56]. Analogously to the costs, the saving of times can sometimes only be determined indirectly (e.g., via the Change Propagation Index (CPI) [57] for ID 1220).

Table 2. KPIs and calculation principles for determining economic targets in the IMF.

ID	Economic Target VALUE	KPI	Calculation/Reference	Unit	Benchmark (R: Reference; A: Alternative)
1000	**Product costs**	Direct material costs (C_{mat})	Gross material costs * Material overheads * Supplier costs * Supplier overheads [55]	[€]	$C_{mat,A} < C_{mat,R}$
1010	**Product quality**	Volume (V)	Classical volume calculation for geometric elements	[cbm]	depends on product
1020	**Product quality**	Feature efficiency ratio (R_{eff})	Number of unused features/Total number of features * 100	[%]	$R_{eff} \rightarrow 0\%$
1030	**Product quality**	Weight (W)	Volume * Density	[kg]	depends on product
1040	**Product costs**	Direct material costs (C_{mat})	Gross material costs * Material overheads * Supplier costs * Supplier overheads [55]	[€]	$C_{mat,A} < C_{mat,R}$
1050	**Process time**	Coordination time (T_{coord})	Time per process (coordination) * Number of repetitions	[h]	$T_{coord,A} < T_{coord,R}$
1060	**Process time**	Product development time (T_{pd})	Time per process (development) * Number of repetitions	[d]	$T_{pd,A} < T_{pd,R}$
1070	**Process costs**	Development costs (C_{pd})	Cost rate * Time per process (develop.) * Number of repetitions	[€]	$C_{pd,A} < C_{pd,R}$
1080	**Process flexibility**	PD capacity flexibility (F_{pdcap})	Share of development capacities saved through outsourcing	[%]	$F_{pdcap,A} > F_{pdcap,R}$
1090	**Process time**	Time for critical path in PD (T_{pdcrit})	Critical path method (CPM) [56]	[d]	$T_{pdcrit,A} < T_{pdcrit,R}$
1100	**Process flexibility**	PD temporal flexibility (F_{pdtemp})	Share of development times saved through parallel development	[%]	$F_{pdtemp,A} > F_{pdtemp,R}$
1110	**Process time**	Time to complete prototype testing (T_{proto})	Critical path method (CPM) [56]	[d]	$T_{proto,A} < T_{proto,R}$
1120	**Product quality**	Product Innovation Index (I)	Product Innovation Index Using Linkograph Analysis [58]	[%]	$I_A > I_R$
1130	**Product flexibility**	Generational Variety Index (GVI)	Design for Variety method [59]	[0;1]	$GVI \rightarrow 0$
1140	**Product quality**	Benefit-Cost Ratio (BCR)	Benefit cost analysis [60]	[%]	$BCR_A > BCR_R$
1150	**Portfolio flexibility**	Market segments coverage ratio (R_{MSC})	Number of market segments covered/number of market segments to be addressed	[%]	$R_{MSC,A} > R_{MSC,R}$
1160	**Process time**	Time for variant derivation (T_{deriv})	Time per process (creation of variants) * Number of repetitions	[h]	$T_{deriv,A} < T_{deriv,R}$
1170	**Product quality**	Failure rate ratio (R_{fail})	Number of failures per time frame/Number of processes per time frame * 100	[%]	$R_{fail} \rightarrow 0\%$
1180	**Process time**	Failure rate ratio (R_{fail})	Number of failures per time frame/Number of processes per time frame * 100	[%]	$R_{fail} \rightarrow 0\%$
1190	**Product quality**	Product reliability (PR)	Share of already tested components	[%]	$PR_A > PR_R$

Table 2. *Cont.*

ID	Economic Target VALUE	KPI	Calculation/Reference	Unit	Benchmark (R: Reference; A: Alternative)
1200	**Process time**	Time for part search (T_{search})	Time per process (part search) * Number of repetitions	[h]	$T_{search,A} < T_{search,R}$
1210	**Process time**	Time for administration (T_{admin})	Time per process (administration) * Number of repetitions	[h]	$T_{admin,A} < T_{admin,R}$
1220	**Process time**	Change Propagation Index (CPI)	Change Propagation Analysis [57]	[0;1]	CPI $\rightarrow$ 0
1230	**Process costs**	Initial development costs (C_{init})	ΣInitial development investment	[€]	$C_{init,A} < C_{init,B}$
2000	**Stock costs**	Safety stock costs (C_{SS})	Safety stock calculation [61]	[€]	$C_{SS,A} > C_{SS,R}$
2010	**Product costs**	Purchasing costs (C_{purch})	Lot size * Costs per Unit	[€]	$C_{purch,A} < C_{purch,R}$
2020	**Process time**	Clarification time (T_{clar})	Time per process (clarification) * Number of repetitions	[h]	$T_{clar,A} < T_{clar,R}$
2030	**Risk**	Supplier diversity ratio (R_{suppl})	Number of different suppliers/Total number of suppliers * 100	[%]	$R_{suppl} \rightarrow 100\%$
2040	**Process time**	Time for supplier management (T_{man})	Time per process (supplier manag.) * Number of repetitions	[h]	$T_{man,A} < T_{man,R}$
2050	**Process flexibility**	Planning accuracy (PA)	Share of variant components in the product family	[%]	$PA_A > PA_R$
2060	**Process costs**	Order costs (C_{order})	Cost rate * Time per process (order) * Number of repetitions	[€]	$C_{order,A} < C_{order,R}$
2070	**Process time**	Order time (T_{order})	Time per process (order) * Number of repetitions	[h]	$T_{order,A} < T_{order,R}$
2080	**Product quality**	Supplier performance indicator	Supplier evaluation method, certifications (f.e. ISO BS/EN ISO 9001:2000)	[%]	depends on method
3000	**Lead time**	Time to start planning (T_{plan})	Critical path method (CPM) [56]	[d]	$T_{plan,A} < T_{plan,R}$
3010	**Lead time**	Time to first variation formation (T_{var})	Critical path method (CPM) [56]	[d]	$T_{var,A} > T_{var,R}$
3020	**Process time**	Time for production steps (T_{prod})	Time per process (production step) * Number of repetitions	[h]	$T_{prod,A} < T_{prod,R}$
3030	**Process costs**	Costs for production steps (C_{prod})	Cost rate * Time per process (prod. step) * Number of repetitions	[€]	$C_{prod,A} < C_{prod,R}$
3040	**Process costs**	Assembly costs (C_{ass})	Cost rate * Time per process (assembly) * Number of repetitions	[€]	$C_{ass,A} < C_{ass,R}$
3050	**Process time**	Time for critical path in testing ($T_{testcrit}$)	Critical path method, CPM [56]	[h]	$T_{testcrit,A} < T_{testcrit,R}$
3060	**Process flexibility**	Production temporal flexibility ($F_{prodtemp}$)	Share of production times saved through parallel testing	[%]	$F_{prodtemp,A} > F_{prodtemp,R}$
3070	**Process costs**	Assembly costs (C_{ass})	Cost rate * Time per process (assembly) * Number of repetitions	[h]	$C_{ass,A} < C_{ass,R}$
3080	**Process flexibility**	Production system flexibility (F_{ps})	Design of Flexible Production Systems [62]	[%]	$F_{ps,A} > F_{ps,R}$
3090	**Process costs**	Machine utilization ratio (R_{uti})	Machine running time/Total capacity * 100	[%]	$R_{uti} \rightarrow 100\%$

Table 2. *Cont.*

ID	Economic Target VALUE	KPI	Calculation/Reference	Unit	Benchmark (R: Reference; A: Alternative)
3100	**Process costs**	Assembly costs (C_{ass})	Cost rate * Time per process (assembly) * Number of repetitions	[€]	$C_{ass,A} < C_{ass,R}$
3110	**Lead time**	Rework time (T_{rw})	Share of rework time saved through increased learning curve	[%]	$T_{rw,A} < T_{rw,R}$
3120	**Lead time**	Degree of automation potential (AP)	Automation potential analysis (APA) [63]	[%]	$AP_A > AP_R$
3130	**Process costs**	Tool investment costs (C_{Tool})	ΣTool investment costs	[€]	$C_{Tool,A} < C_{Tool,R}$
3140	**Process costs**	Inventory holding costs (C_{IH})	(Storage Costs + Employee Costs + Opportunity Costs + Depreciation costs)/Total value of annual inventory	[%]	$C_{IH,A} < C_{IH,R}$
3150	**Process costs**	Set up costs (C_{set})	Cost rate * Time per process (set up) * Number of repetitions	[€]	$C_{set,A} < C_{set,R}$
3160	**Process time**	Set up time (T_{set})	Time per process (set up) * Number of repetitions	[h]	$T_{set,A} < T_{set,R}$
3170	**Process flexibility**	Production temporal flexibility ($F_{prodtemp}$)	Share of production times saved through less set up changes	[%]	$F_{prodtemp,A} > F_{prodtemp,R}$
4000	**Process time**	Time for offer preparation (T_{offer})	Time per process (offer preparation) * Number of repetitions	[h]	$T_{offer,A} < T_{offer,R}$
4010	**Quality of customer loyality**	Customer Satisfaction Score ($CSAT_C$)	Customer satisfaction score evaluation [64] with focus on the influence of customer configurability	[%]	$CSAT_C \rightarrow 100\%$
4020	**Quality of customer loyality**	Customer Satisfaction Score ($CSAT_R$)	Customer satisfaction score evaluation [64] with focus on the influence of fast reaction to customer requirements	[%]	$CSAT_R \rightarrow 100\%$
4030	**Turnover**	Turnover (TO)	(Sales price * Sales volume) − Sales deductions	[€]	$TO_A > TO_R$
4040	**Portfolio flexibility**	Market segments coverage ratio (R_{MSC})	Number of market segments covered/number of market segments to be addressed	[%]	$R_{MSC,A} > R_{MSC,R}$
4050	**Portfolio flexibility**	Market segments coverage ratio (R_{MSC})	Number of market segments covered/number of market segments to be addressed	[%]	$R_{MSC,A} > R_{MSC,R}$
4060	**Turnover**	Turnover per product variant (TO_{pv})	Cost difference for the determination of cannibalization effects	[€]	depends
4070	**Process costs**	Time for trainings in sales ($T_{trainsal}$)	Time per process (trainings in sales) * Number of repetitions	[h]	$T_{trainsal,A} < T_{trainsal,R}$
4080	**Product costs**	Savings due to process costs from all life phases (C_{sav})	Σprocess costs (development, procurement, production, sales, service)	[€]	$C_{sav,A} > C_{sav,R}$
4090	**Time to Market**	Savings due to process time from previous phases (T_{sav})	Σprocess time (development, procurement, production, sales)	[d]	$T_{sav,A} > T_{sav,R}$

Table 2. *Cont.*

ID	Economic Target VALUE	KPI	Calculation/Reference	Unit	Benchmark (R: Reference; A: Alternative)
5000	**Process costs**	Change Propagation Index (CPI)	Change Propagation Analysis [57]	[0;1]	CPI → 0
5010	**Quality of customer loyality**	Change Propagation Index (CPI)	Change Propagation Analysis [57]	[0;1]	CPI → 0
5020	**Process costs**	Intact module costs (C_{im})	Share of service costs through maintenance of intact modules	[%]	$C_{im,A} < C_{im,R}$
5030	**Process costs**	Specialized tool costs (C_{tool})	ΣCosts for spezialized tools	[€]	$C_{tool,A} < C_{tool,R}$
5040	**Process costs**	Cost for trainings in service ($C_{trainser}$)	Cost rate * Time per process (trainings in service) * Number of repetitions	[h]	$C_{trainser,A} < C_{trainser,R}$
5050	**Process time**	Service time (T_{ser})	Share of service time saved through increased learning curve	[%]	$T_{ser,A} < T_{ser,R}$
5060	**Process time**	Time for failure diagnosis (T_{diag})	Time per process (failure diagnosis) * Number of repetitions	[h]	$T_{diag,A} < T_{diag,R}$
5070	**Process time**	Time for disassembly (T_{dis})	Time per process (disassembly) * Number of repetitions	[h]	$T_{dis,A} < T_{dis,R}$

The target values of quality and flexibility also tend to be difficult to quantify directly. Here, existing indices from literature are often used to support a relative comparison of alternative product architecture concepts, such as the Product Innovation Index (I) [58] (ID 1120), the Generational Variety Index [59] (ID 1130), or the Benefit-Cost-Ratio (BCR) [60] (ID 1140).

The time dependency of economic impacts has already been investigated in comprehensive studies based on several project examples (e.g., in [11]). Within this context, the classification could be made into short-term (appearance less than 1 year after implementation), medium-term (appearance between 1 to 3 years after implementation) and long-term (appearance more than 3 years after implementation). This information is linked together with the KPIs in the form of sub-BBDs with the economic effects in the Sys-IMF to complete the implementation of the IMF in SysML according to the extended data model shown in Figure 3. The mathematical integration via MATLAB, for example, is not expedient here—separate calculation models should be used for this due to the large amount of data. Figure 7 shows the integration of the KPIs and the temporal information by means of BBD using the example of the order costs from the procurement phase.

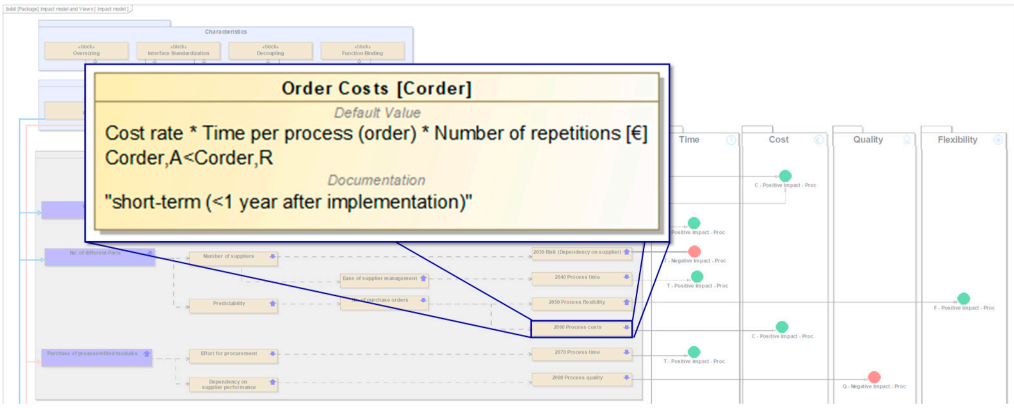

Figure 7. Implementation of the new KPIs and the information about the temporal occurrence of effects in the Sys-IMF using the example of order costs (ID 2060).

4.4. Maintenance and Import of New Data

The initial implementation of the IMF in SysML with all system elements represents only the first step in designing and using the accumulated knowledge base on the effects of modularization. In the second step, a two-way information flow is to be developed in order to be able to feed the Sys-IMF with new data as well and thus successively enrich the knowledge base. For this purpose, an interface to MS Excel is being developed. This enables broad applicability with a common tool and allows intuitive use even for users with limited knowledge of SysML. Figure 8 shows the data flow with the respective interfaces and the associated software.

The Sys-IMF can be seen as the basic database in which all effects and system elements are stored and related to each other (Figure 8, left). The export to MS Excel allows the visualization of the model (Figure 8, center) as well as the integration of empirical data through linked maintenance tables via the associated IDs (Figure 8, right). Within these tables, users will be able to enter values for the effects in the future, which will be collected within the framework of empirical studies on modularization. These are then mirrored back into the Sys-IMF through an import interface (Figure 8, below). The closed loop via an MS Excel import/export thus enables low-effort feeding of the model. In the long term, the aim is to increase the validity and informative value of the knowledge base as the data increases. For three modularization projects already analyzed, the data were entered into the model as examples (Figure 9).

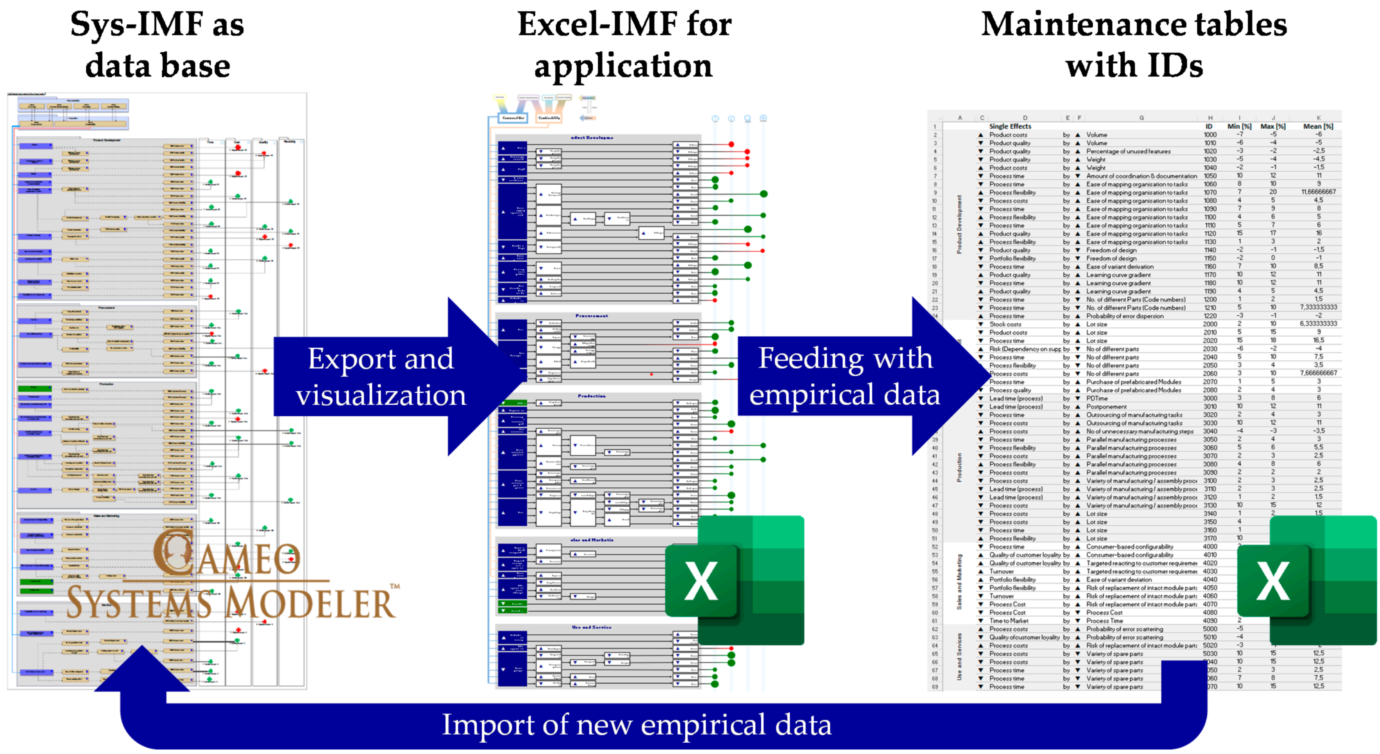

Figure 8. Data flow between Sys-IMF, Excel-IMF and maintenance tables for continuous and dynamic data management.

#	Name	by	Owner	Project 001	Project 002	Project 003
24	2000 Stock costs	Lot size	Procurement	10.0	15.0	0.0
25	2010 Process costs	Lot size	Procurement	30.0	15.0	10.0
26	2020 Process time	Lot size	Procurement	5.0	10.0	35.0
27	2030 Risk (Dependency on supplier)	No. of different Parts	Procurement	0.0	5.0	5.0
28	2040 Process time	No. of different Parts	Procurement	10.0	10.0	25.0
29	2050 Process flexibility	No. of different Parts	Procurement	5.0	5.0	10.0
30	2060 Process costs	No. of different Parts	Procurement	10.0	5.0	25.0
31	2070 Process time	Purchase of preassembled modules	Procurement	0.0	25.0	10.0
32	2080 Process quality	Purchase of preassembled modules	Procurement	0.0	30.0	5.0

Figure 9. Generic table and data collection in Sys-IMF for three analyzed modularization projects for the life phase of procurement.

The values entered in this case are only specified as percentages (e.g., 5% in project 001 for the process time reduction (ID 2020)) but can also take on absolute values from now on due to the provision of the KPIs. However, a statistical evaluation requires a larger amount of data in order to enable truly valid statements even under different boundary conditions and to form mean values or standard deviations. The initial creation of the Sys-IMF with associated import/export functions in MS Excel forms the basis for this analysis and enables a simple and low-effort enrichment of the knowledge base and thus the long-term generation of a powerful tool in the context of the design and evaluation of modular product architecture concepts. The application of the extended IMF incorporated in SysML as a decision support is presented in the next section.

5. Application of Sys-IMF for Decision Support in Modular Product Family Design

Following the extension and SysML implementation of the IMF, its application to support the evaluation of modular product architecture concepts is introduced and validated by means of an application example. The overall procedure consists of two main phases and is illustrated in Figure 10.

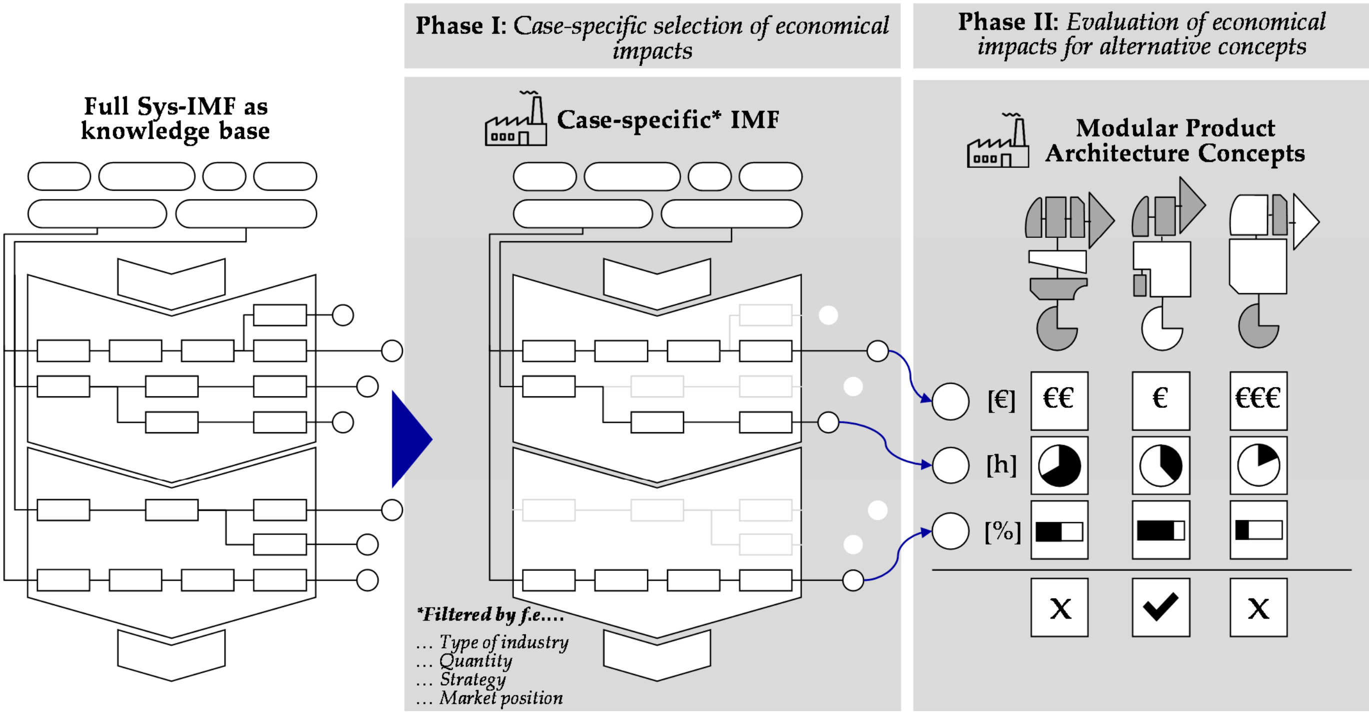

Figure 10. Illustration of the approach to support the evaluation of alternative modular product architecture concepts.

In Phase I, the Sys-IMF is used to determine the case-specific effects for the particular use case. For this purpose, the complete model is exported to MS Excel via the presented interface, and the case-specific effects of modularization are extracted from the knowledge base using a filter function. For the extracted effects, the stored KPIs are then used for a comparative evaluation of alternative product architecture concepts (Phase II). To this end, the values are determined according to the stored calculation methods and compared for the individual modular concepts. The selection of the best possible alternative based on the evaluation represents the result of the procedure. The method is presented and applied below using real product architecture concepts from a modularization project from Siemens. For reasons of confidentiality, the example is anonymized, but the values determined correspond to reality.

5.1. Use Case

In the application example, a product family of medium-voltage electric motors is modularized. The industry is characterized by a strong correlation between order volumes and oil and gas prices, which means that day-to-day business is very volatile. In times of low order density, highly individualized orders are therefore also accepted, which over the years has led to a historically grown product portfolio with very high internal variety. The number of units sold is around 2000 product variants per year and the company's strategy is equal parts Engineer-to-order (EtO) and Make-to-order (MtO).

In order to reduce internal product variety, a building kit (Baukasten) for the product family of medium-voltage electric motors is being developed within the scope of a modularization project. The aim here is to generate the maximum possible variety of offers using a specific set of components and to keep the internal effort as low as possible by means of a predefined configuration logic (for an overview of the various modular product structuring strategies, see [4]). In the context of the application, for the sake of clarity, the bearing assembly of the motors is considered, and three alternative modular product architecture concepts are developed (Figure 11). The pictures of the alternatives are for illustration purposes only, while the figures represent real values.

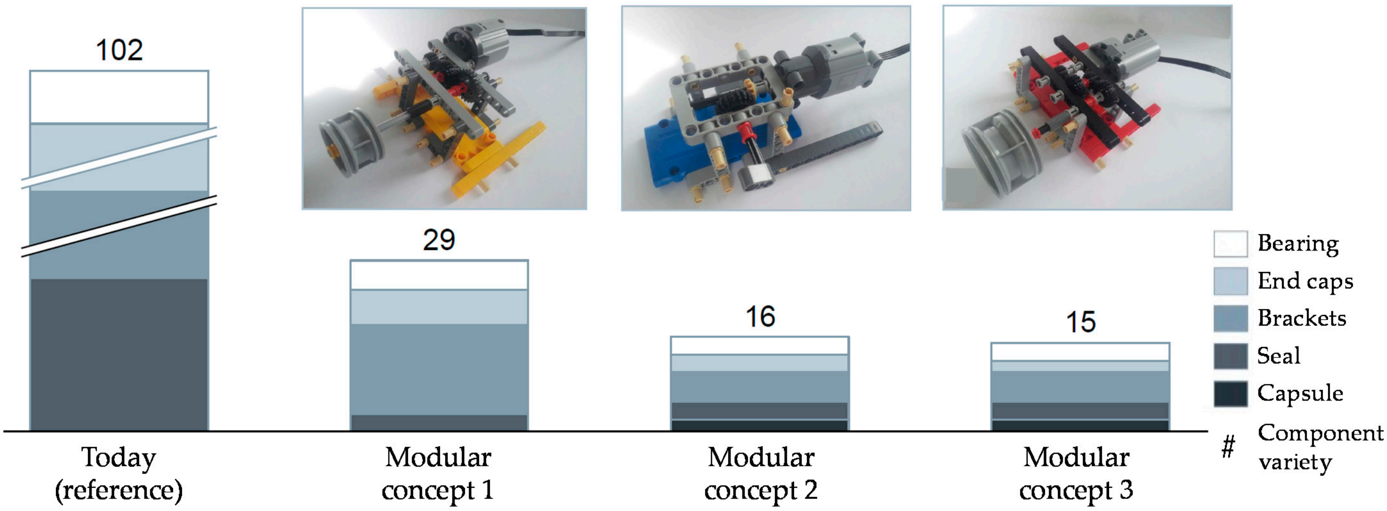

Figure 11. Comparison of the component variety of the developed modular concepts and the reference concept of the medium voltage electric motors (images for visualization only).

As can be seen in the diagram, the number of variants is greatly reduced by using a building kit as a product structuring strategy in all three concepts through standardization measures. The concept alternatives developed differ primarily in the varying technical implementations for the type and number of bearing arrangements. Concept 1 has about twice as many variant components as the other two concepts, 2 and 3. The last two alternatives have only a marginal difference in terms of technical implementation and component variance. For the knowledge-based and case-specific evaluation of the alternative product architecture concepts, the presented 2-phase approach is applied using the extended IMF.

5.2. Phase I: Case-Specific Selection of Economical Impacts

In a first step, the information on the company-, project- and product-specific boundary conditions is used to filter the case-specific impacts from the Sys-IMF. For this purpose, Sys-IMF is exported to MS Excel, and the effects of modularity are extracted using an implemented filter option for the stored boundary conditions (Figure 12).

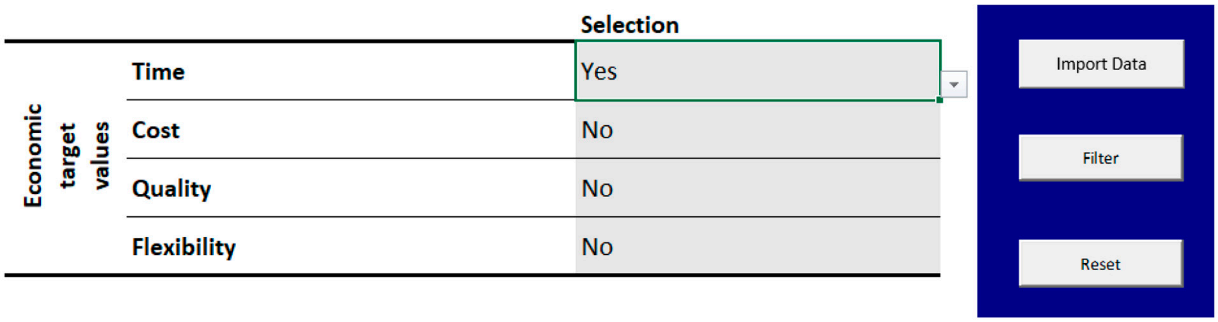

Figure 12. Implemented filter function for the case-specific selection of effects of modularization (here using the example of the four economic target values).

Typical input values include, e.g., type of industry, quantity, strategy or market position. However, they also project-specific parameters, such as project budget, project duration or the number of project participants, which are stored in the model and can be entered as boundary conditions. If the desired economic targets are already known, they can be selected directly at the level of the economic target values. In this way, the user can not only display case-specific effects, but also select specific savings potentials based on predefined targets. The result of this first phase is a filtered IMF, which shows the main impact chains in relation to the respective boundary conditions and targets. For the application example, a total of 22 impact chains are filtered from the model (see Figure 13).

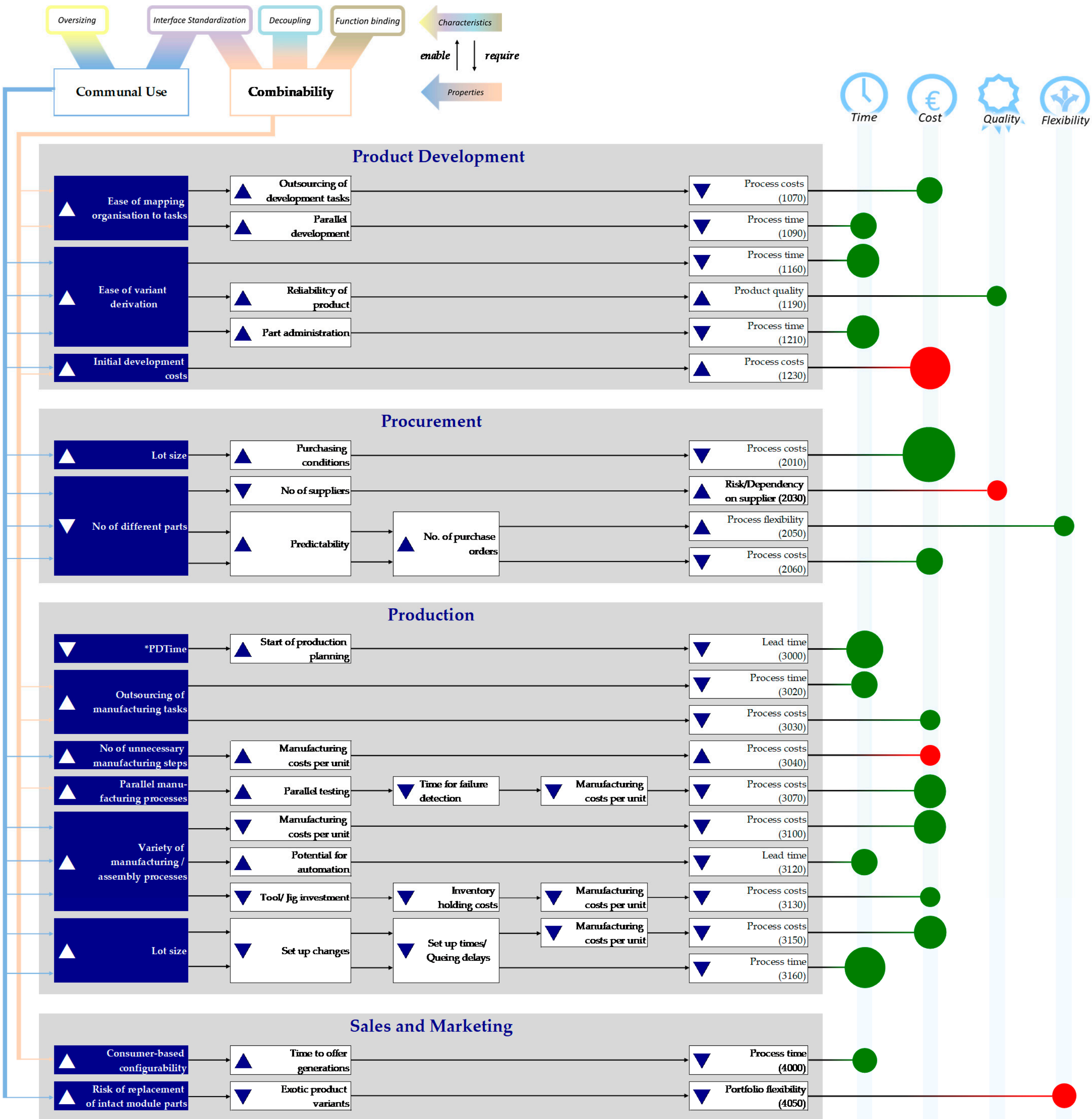

Figure 13. Visual representation of the filtered IMF with the case-specific impact chains for the application example.

For visual analysis as well as for less effort handling and calculation of the KPIs, the results are generated in MS Excel. This represents a key requirement in the context of the practical applicability of the extended IMF. In addition, this enables interdisciplinary use of the model, which is particularly important for decision-making in the context of modular product families. In many cases, a heterogeneous team from different disciplines and with varying previous experience is involved in this early design stage in context of modularity decisions [16].

The filtered IMF for the product family of the bearing assembly of medium-voltage electric motors in Figure 13 shows the impact chains that have already been identified in past projects under the same boundary conditions. The size of the bubbles on the right-hand side provides a qualitative measure of the potential savings (green), respectively, the expenses or disadvantages (red) of the particular effect. This information is stored in the IMF from more than 10 past modularization projects and is constantly growing. The larger the bubble, the greater the savings for this effect under similar boundary conditions. So far, these have only been included in the knowledge base qualitatively as a percentage, but in the future, they can also be partially recorded quantitatively by depositing the KPIs. Thus, using the knowledge base of the extended IMF, the impacts can not only be visualized, but also used to support the selection and evaluation of KPIs for quantification. This represents the transition to the second phase of the methodological approach to the application of the extended IMF.

5.3. Phase II: Evalution of Economical Impacts for Alternative Modular Concepts

In the second phase, the alternative product architecture concepts are evaluated with respect to the filtered effects from the knowledge base and compared with each other. For this purpose, the calculation bases from Table 2 are used to determine the values for the respective concept alternatives. Since the effects of modularity exhibit a time-dependent behavior, the savings and expenditures in the example are laid out over a period of 3 years. This ensures that the long-term effects are also taken into account in the assessment [61–65]. The temporal determination is also of particular relevance for the determination of the saved process costs, since the numbers of repetitions are time-dependent. In addition, this also allows the timing of the ROI to be determined. The calculated results for the KPIs of the selected economic target values are shown in Table 3 for the three concepts. For confidentiality reasons, only the difference to the reference product architecture is shown, and the respective direction is color-coded.

In the development phase (ID 1xxx), significant savings can be achieved with all three concepts due to the reduced number of variants. For example, the development times for administration (1210) and variant generation (1160) are drastically reduced, especially in concepts 2 and 3, which in turn have a direct impact on the variety-induced complexity costs. The initial development costs (1230) for the conceptual design, engineering and implementation of the respective alternatives have a negative impact here, but must be taken into account for the overall calculation. Considering the benefits from the development alone would make this calculation a negative business case, but seen across the entire value chain, it is not. In the present use case, the main advantages arise in the procurement phase (ID 2xxx). Here, procurement costs (2010) can be significantly reduced, which can be attributed to the economies of scale resulting from higher quantities due to standardization measures. As already shown in the filtered IMF in Figure 13, the proportionally largest savings for all concepts result here. Concept 3 in particular can generate the greatest cost benefits. However, the process flexibility (2050) additionally increases significantly due to the variant reduction. Here, the higher quantities enable a change in procurement strategy and an increase in make-or-buy flexibility. In the production phase (ID 3xxx), significant advantages are also achieved through the modular concepts. In particular, the saving of development time means that planning can start earlier (3000), and thus the overall lead time becomes more predictable and shorter. Contrary to the knowledge-based prediction from the filtered IMF, the investment costs for the tools (3130) increase for all three concepts.

Table 3. Comparing the modular product architecture concepts from the use case using the KPIs from the extended IMF.

ID	Economic Target Value	KPI	Concept 1	Concept 2	Concept 3
1070	**Process costs**	Development costs (C_{pd}) [NC-Programming]	−5 k$	−27 k$	−29 k$
1090	**Process time**	Time for critical path in PD (T_{pdcrit})	−20 d	−80 d	−80 d
1160	**Process time**	Time for variant derivation (T_{deriv})	−110 h	−140 h	−150 h
1190	**Product quality**	Product reliability (PR)	+25%	+40%	+45%
1210	**Process time**	Time for administration (T_{admin})	−200 h	−510 h	−560 h
1230	**Process costs**	Initial development investment costs (C_{init})	+140 k$	+164 k$	+176 k$
2010	**Product costs**	Purchasing costs (C_{purch})	−500 k$	−920 k$	−1180 k$
2030	**Risk**	Supplier diversity ratio (R_{suppl})	±0%	+10%	+15%
2050	**Process flexibility**	Planning accuracy (PA)	+72%	+84%	+85%
2060	**Process costs**	Order costs (C_{order})	−5 k$	−7 k$	−7 k$
3000	**Lead time**	Time to start planning (T_{plan})	−30 d	−55 d	−60 d
3020	**Process time**	Time for production steps (T_{prod})	−40 h	−100 h	−120 h
3030	**Process costs**	Costs for production steps (C_{prod}) [Testing]	−2 k$	−5 K$	−6 k$
3040	**Process costs**	Assembly costs (C_{ass})	−5 k$	−12 k$	−12 k$
3070	**Process costs**	Assembly costs (C_{ass})	−5 k$	−8 k$	−8 k$
3100	**Process costs**	Assembly costs (C_{ass})	−3 k$	−10 k$	−10 k$
3120	**Lead time**	Degree of automation potential (AP)	+10%	+15%	+40%
3130	**Process costs**	Tool investment costs (C_{Tool})	+80 k$	+130 k$	+153 k$
3150	**Process costs**	Set up costs (C_{set})	−17 k$	−27 k$	−32 k$
3160	**Process time**	Set up time (T_{set})	−800 h	−1270 h	−1500 h
4000	**Process time**	Time for offer preparation (T_{offer})	−80 h	−90 h	−90 h
4050	**Portfolio flexibility**	Market segments coverage ratio (R_{MSC})	±0%	−5%	±0%

This is due to the fact that the new components also require new tools (in this case, new casting tools), which must first be procured. In the long run, however, fewer tools are needed, so that in the overall picture this positively affects the ongoing production costs. In addition to the process costs saved, there are also other advantages in production that cannot be quantified directly but must nevertheless be taken into account. Thus, all three concepts enable increased automation of production processes (3120), which can lead to further follow-up effects during implementation. Modularization is hence an enabler in the sense of the domino effect for further savings. In Sales and Marketing (ID 4xxx), process time savings result from faster quotation generation (4000)—especially due to the predefined configuration logic. Additional potential can be tapped here in the future with the help of a configurator. However, the design of the configurator requires additional initial efforts that are not included in the model. This calculation shall be supplemented as necessary. When selecting modular concept alternatives, it is also essential that the external variety of offers is not or only marginally restricted. For this reason, portfolio flexibility (4050) is particularly important, as it specifies the extent to which the variety of offers required by the customer is restricted or even extended. The value is only slightly negative for concept 2, so that it can be assumed here that the required external variety can be largely covered by all three concepts. The visual comparison of the summed values for the target values of cost, time (TTM), quality and flexibility are shown in Figure 14.

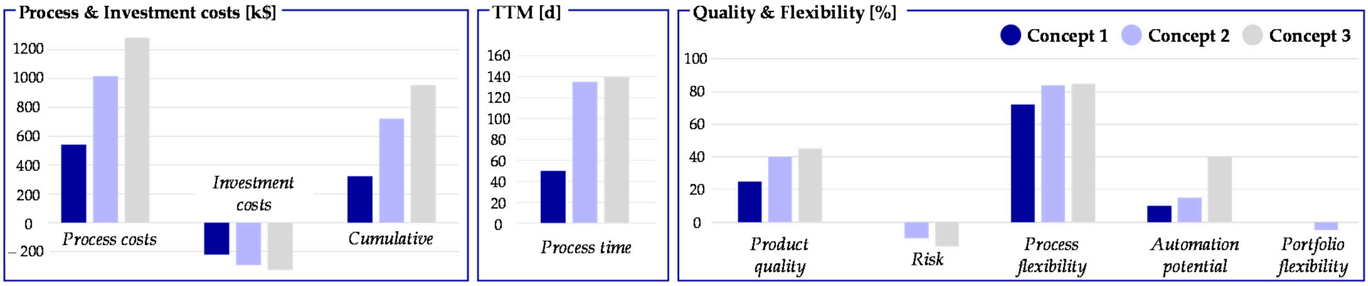

Figure 14. Final comparison of the concepts for the economic target values (positive values represent savings).

The process times, which have a direct impact on costs in the sense of TD-ABC, are integrated into the calculation of process costs. In the case of time-to-market (TTM), in particular the times are accumulated which relate to savings due to shortened development and production times. Quality and flexibility are specified as percentages in the model but enable a goal-oriented comparison of the alternatives for the target variables that are difficult to quantify. Based on the visual comparison of the determined values, concept alternative 3 can be clearly identified as the best concept. Although the initial costs are the highest with this concept, by far the most monetary savings are achieved over 3 years. In terms of pure costs, this results in an ROI estimated by the experts of just 11 months after successful implementation. However, even the non-monetary targets clearly point to this concept. Although the risk of dependence on suppliers is increased with this concept, the other potential savings clearly outweigh this. The result of this second phase is a selected modular product architecture concept for implementation in the company.

6. Discussion

In the following, the previously generated results are discussed in relation to the stated research question. First, the modeling of the IMF with KPIs, boundary conditions and temporal information in SysML is critically considered, and then the possible interactions with the Sys-IMF are discussed in the context of the concept evaluation.

6.1. Modeling of the IMF in SysML

Modeling the IMF in Cameo Systems Modeler provides significant advantages over the static representation. Through SysML modeling, it is possible to ensure an extensible, consistent and dynamic representation of the IMF. It is possible to interact with the model and additional information can be added to the individual elements of the IMF without endangering the clarity of the model itself. Thus, additional information can be stored exactly at the point in the model where it is needed. To view the IMF and all additional information that is available and relevant, it is no longer necessary to use several different media. All information can be accessed directly in the Cameo model, which significantly increases the usability and applicability of the IMF.

In addition, it must be taken into account that the IMF will be supplemented with further empirical data in the future in order to enrich the knowledge base with additional knowledge and make it more valid. Currently, the model has over 70 impact chains, which could be confirmed, refuted or specified in further studies. In the future, this database must be further enriched in order to be able to make an even clearer statement with regard to the expressions (bubble size) of the effects. The interface to MS Excel is essential here, since it enables low-effort maintenance and filling of the data even for users without MBSE knowledge.

In the block definition diagram, relationships between effects can still be revised or effects can be added to the IMF without major effort. Boundary conditions can also be dynamically adjusted and extended. The boundary conditions were previously tabulated in various different tables or only partially assigned to the effects (e.g., as in [15]). By bundling the information, it was also possible to eliminate redundant boundary conditions. This change to the relationships only needs to be entered at one point in the model in the Cameo Systems Modeler and is then automatically applied throughout the model.

In addition to consistent data storage, the modeling also enables consistent linking of effects from modular properties to economic targets. In the current version, the model still has limitations with regard to the mathematical linking of the various blocks. Here, with the implementation of the KPIs as sub-BDD, the first rules could already be established, which should be used for further simulations, e.g., with the help of MATLAB or SIMULINK.

6.2. Interaction with the Sys-IMF as Decision Support for Concept Decisions

The application of the Sys-IMF was carried out as part of a single case study using the example of a product family of bearing assemblies of medium voltage electric motors. Here, the interaction with Sys-IMF could be checked and evaluated with experts from industry. A major advantage of the presented method lies in particular in its ease of use and direct access to an extensive database. This allowed users to consider impact chains when evaluating the modular concepts that would not have been taken into account in other assessments. In particular, non-monetary savings are often difficult to measure, in many cases ambiguous, and often only available as tacit knowledge. By applying the method using the IMF as knowledge base, these implicit aspects become explicitly available. This also represents a significant advantage over existing methods of decision support, which either focus only on existing cost accounting types or remain too unspecific.

A shortcoming of the current use of the Sys-IMF lies in the sole consideration and evaluation of already existing modular product architecture concepts. The feedback of the assessment results to derive specific measures to influence the product architecture is currently not directly possible. This is a multiobjective optimization problem, which has several solutions and could be solved using suitable algorithms (e.g., genetical algorithms) or machine learning methods. The basis for this has already been created with the SysML model, since consistent modeling and traceability of the economic effects to the modular product architecture properties is possible here. However, it is already possible to make initial statements regarding the preferred modular product structuring strategy (commonality = tendency towards standardization/platform; combinability = tendency towards building kit).

Challenges in using the IMF as a decision support tool include the duplication of process costs and associated process times. The integration of KPIs, for example, as well as the application has shown that some effects influence each other in the sense of the TB-ABC method. Thus, many cost effects are generated directly from the process times (e.g., 3020 and 3030), which are partly not stored consistently in the previous model. This circumstance should be taken into account in further investigations in order to reduce redundant values and the respective calculation efforts. In this context, a clearer distinction should be made between one-time costs (investment costs) and recurring costs (process costs). Both types of costs are included in the extended IMF but are not currently identified as such. Consideration of both types and the cumulative calculation are important as final decision support and should be maintained. Overall, the developed procedure using the Sys-IMF thus provides essential support for the selection of relevant assessment criteria and the evaluation of modular product architecture concepts.

7. Closing Remarks and Future Work

This publication describes a methodical approach to support concept decisions in the development of modular product architectures. The central element of the approach is the extended Impact Model of Modular Product Families (IMF), which maps the effects of modularity on economic target variables based on experience over several decades and is used for the selection of case-specific criteria for the evaluation of the concepts. To enable consistent, extensible and dynamic data modeling as well as utilization of this knowledge base, the IMF was implemented in SysML using the Cameo Systems Modeler and the new Sys-IMF has been generated. As an extension, suitable KPIs were added to the purely qualitative impact chains in the model to enable the quantitative determination of the effects for case-specific applications. This case-specific applicability was additionally enabled by the integration of essential boundary conditions as well as time dependence into the model. In addition, an interface to MS Excel has been created to enable low-effort filling and maintenance of the Sys-IMF. The process allows both the import of new data and the export of existing data (closed-loop). The export function is mainly essential for the visual analysis and the methodical procedure for selecting case-specific effects of modularization. The two-phase approach aims at filtering the case-specific impact chains from the extended IMF and evaluating them according to the stored KPIs for the different concepts. The procedure was applied and subsequently evaluated using the example of a product family of medium-voltage electric motors. In the process, a total of 22 impact chains from four different life phases could be extracted from the model and used for the subsequent concept evaluation. The review of the case study has shown that especially the consideration of different and often hardly quantifiable economic target values generates a great advantage in the evaluation of alternative concepts in this early phase of product development. Limitations currently relate primarily to the mathematical linking of the product structure properties and the economic target values. A foundation has already been laid in this work with the integration of KPIs, which should be further developed and used for simulations in future work. In addition, the integration of modularization methods is the subject of current research, which in the long term should make the model a holistic and universal tool for modular product family design (initial approaches in [10]). In this context, the data basis needs to be further strengthened and the model enriched with additional empirical data. The interface developed supports this venture and contributes to the ability of other researchers in this area to use the visual knowledge base.

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