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Towards an Approach for the Target-Size-Oriented Selection and Adaptation of Methods for the Development of Modular Product Families

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Abstract: Increasing customer demands and intensifying competition lead many companies to expand their product portfolios continuously, posing challenges for manufacturing firms. Modular product families offer a solution by maintaining external variety while reducing internal variety. Modular product families impact all product life phases and economic targets like time, cost, quality, and flexibility. However, selecting methods for developing modular product families based on economic objectives is challenging due to method intricacies, inconsistent documentation, and vague economic goal addressing. This paper proposes a method selection and adaptation approach for modular product family development to address this problem. This approach uses a methodstep-database from our own preliminary work to support the target-size-oriented adaptation.

Keywords: product development, method selection, modular product families, product family design, impacts of modularity, module drivers

1 Introduction

Increasing customer requirements and growing competitive pressure are leading to a constantly growing product portfolio for many companies. This presents manufacturing companies with more and more challenges. Modular product families provide a way of maintaining external diversity and also reducing internal diversity, thereby reducing expenditure, including in form of complexity costs (Krause and Gebhardt, 2023). Modular product families are described by the properties commonal use and combinability (Salvador, 2007). In commonal use, modules can be used in different product variants and across product families. This is made possible by oversizing and interface standardization. The combinability of modules enables the configuration of different product variants based on a fixed set of modules. Modules can be designed to be combinable by standardizing the interfaces, linking functions and allowing them to be easily decoupled from one another. Modular product families can be used to achieve different impacts in all product life phases and on the target variables of time, costs, quality and flexibility. A large number of methods for developing modular product families can be found in the literature, some of which give different reasons for creating modules (Otto et al., 2016). Due to the inconsistent documentation and the vague addressing of economic objectives, the selection based on economic objectives is difficult. Although the comparisons of methods for developing modular product families that already exist in the literature (for example (Daniilidis et al., 2011; Hölttä, 2004)) provide a first step in the right direction, the addressing of different economic objectives has not yet been included in the comparison criteria. Previous work has shown how the module-forming steps of methods for the development of modular product families can be described in a standardized way and how they can be linked to an impact model of modular product families (IMF) in order to show their specific impacts (Schwede et al., 2022). This paper now presents a procedure for using this methodstep-database to enable a target size-oriented application or adaptation of methods for the development of modular product families. The state of the art first presents some methods for developing modular product families. The impacts of modular product families are also discussed. The research gap is derived from the state of research. In the course of this, initial results from our own preliminary work to close the research gap are presented. Chapter 4 builds on the research results to date to provide a methodical approach for the selection and adaptation of methods, and the individual phases are then discussed in Chapter 5. The paper concludes with an outlook for future research topics in this area.

2 State of Research

This chapter presents the relevant state of research in this subject area. It concludes by identifying a research gap.

2.1 Methods for the Development of Modular Product Families

Many methods have been developed in recent decades for the development of modular product families. These methods include the essential steps: Decomposition of an existing product family to the component level, analysis of the components and then module formation based on the analysis (Pimmler and Eppinger, 1994). Modules can be formed for different reasons, whereby a basic distinction is made between technically functional and product-strategic module formation (Krause and Ripperda, 2013). Basic methods for the development of modular product families are the methods of Erixon, Stone and Pimmler&Eppinger (Erixon, 1998; Pimmler and Eppinger, 1994; Stone, 1997). Erixon uses product-strategic module drivers for module formation in its Modular Function Depolyment (MFD) method (Erixon, 1998). Stone's module formation is based on the application of different technical-functional heuristics (Stone, 1997). Pimmler and Eppinger use Steward's Design Structure Matrix (DSM) to illustrate the coupling between components and recommend a technical-functional module formation of components that are strongly linked to each other and a module section between components with little or no links (Pimmler and Eppinger, 1994; Steward, 1981). There are many further developments and adaptations of these methods. For example, there are methods such as Pimmler and Eppinger that use the DSM to document analyses between elements and use them as a basis for module formation (Browning, 2016). Lanner and Malmquist provide a widespread example of the use of the DSM. In their method, they use an adapted DSM to take technical and economic aspects into account when forming modules (Lanner and Malmqvist, 1996). Building on the approach of Pimmler and Eppinger, Huang and Kusiak present the design matrices interaction matrix and suitability matrix (Huang and Kusiak, 1998). The interaction matrix records the interactions between components. The suitability matrix shows which components are suitable for forming a module. These matrices are combined to form a modularity matrix. Jiao and Tseng present a method for the development of modular product family architectures for mass customization (PFA) (Jiao and Tseng, 1999). The method combines functional, physical (manufacturability) and technological perspectives. Based on customer requirement analyses, design matrices are used for technical functional modularization. The modules are then economically evaluated, which results in the final product architecture. Other methods are based on Erixon, whereby the idea behind module formation is mainly used. Erixon has established the so-called module drivers. For example, Kohl has included safety aspects and requirements in his method called Safety-oriented Modular Function Deployment in the original Erixon Module Indication Matrix (Kohl et al., 2016). Some methods combine the basic methods with each other. Blackenfelt transfers the information from Erixon's method into the DSM format (Blackenfelt, 2001). With the help of the DSM, the number of components is reduced by combining highly dependent components. By applying the MFD, customer requirements, technical and strategic aspects are included in the modularization process. The Integrated PKT Approach for the Development of Modular Product Families also includes technical-functional and product-strategic aspects (Blees et al., 2010; Krause and Gebhardt, 2023) after a variant-oriented product design is carried out, a technical-functional method for developing modular product families is first applied, for example the DSM. Subsequently, network plans are created for all product life phases, in which modules are strategically formed on the basis of module drivers and module driver characteristics. The technically functional module formation is incorporated into the product development network. Finally, the individual networks are harmonized.

2.2 Impacts of Modular Product Families

Modularization brings with it a variety of impacts that can influence the entire product life. The impacts of modular product families are documented in the literature. For example, empirical impacts have been collected using surveys (e.g. (Lau Antonio et al., 2007; Shi et al., 2023)), case studies have been conducted (e.g. (Fixson, 2007; Galvin et al., 2020)) or literature analyses have been carried out (e.g. (Harland and Uddin, 2014)). The results of the content are partly presented in impact models (e.g. Pakkanen, 2015; Rice et al., 2023)). The impact model of modular product families (IMF) was developed on this basis, summarizes the research work and is continuously validated in current research through company surveys (Schwede et al., 2022; Schwede et al., 2019, Hackl et al., 2020). It presents the impacts of modular product families across the life phases of product development, procurement, production, sales and service. The impacts on economic target variables such as time, costs, quality and flexibility are also listed in the IMF. The input variables in the model are the properties and characteristics of modularization. A section of the IMF with two example impact chains is shown below:

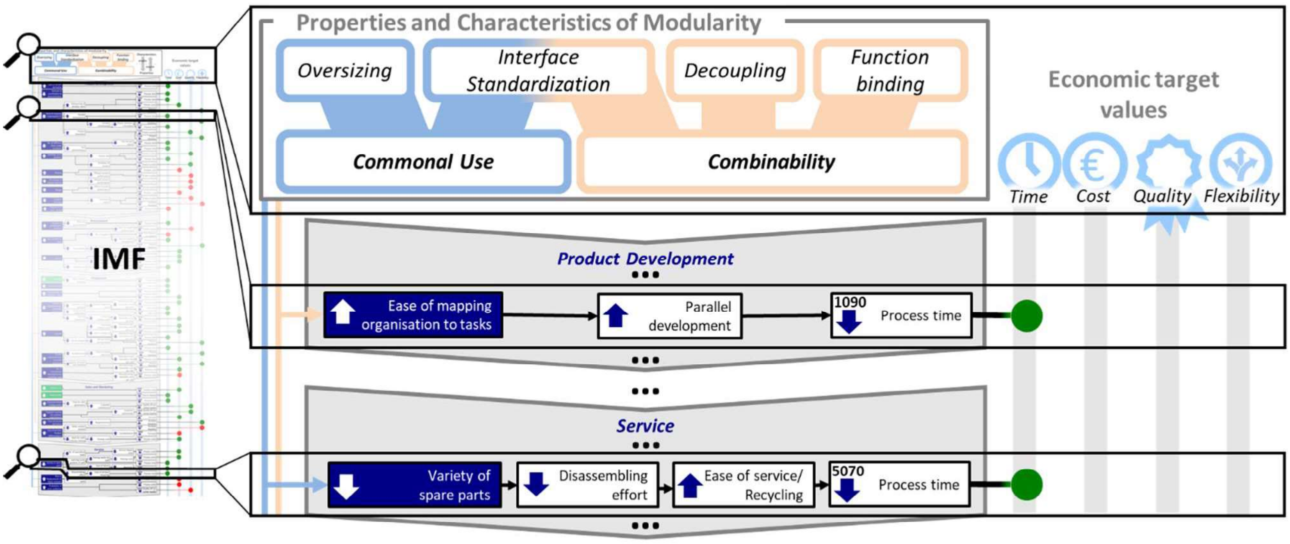

Figure 1: Excerpt from the Impact Model of Modular Product Families (IMF) (according to (Schwede et al., 2022))

The impact chain no. 1090 shows that modularization can enable a parallel development instead of a sequential approach, which can shorten the resulting process time. The duration of development is therefore no longer influenced by the fact that one module has to be completed before the next can be developed. Decoupling, function binding and interface standardization enable combinability: module boundaries are more clearly defined and separated, can be better decoupled and thus also better and more flexibly reassembled into product variants. In the product development phase, configurability enables the organization of a company to be better aligned with the product architecture. This interdependency presented here was originally taken from Ericsson and Baldwin when the model was created (Baldwin and Clark, 2000; Ericsson and Erixon, 1999). Ongoing research has confirmed this causal relationship, particularly in companies that are active in mechanical and plant engineering, that produce in small batches and series production and that have CTO or ETO supply chain strategies. The Critical Path Method (Levy et al., 1963) can be used at this point to calculate the savings in process time. This is applied once for the initial situation and then estimated for concepts, resulting in a trend for the impacts. This is applied once for the initial situation and then estimated for concepts, resulting in a trend for the impacts.

The impact chain no. 5070 shows an advantage of the common use of modules. If more modules are used across product families, the number of spare parts is reduced proportionally. There is no longer so much variance that has to be taken into account when disassembling, which simplifies the service. This also has a positive impact on process time. This impact chain has also been confirmed mainly by companies from the mechanical and plant engineering sector, but is also relevant in the aviation industry. This impact chain was originally documented in (Boer, 2014), for example.

The generic IMF contains a total of 67 impact chains. Literature-based key figures were assigned to these impact chains in a database in order to enable quantification based on this qualitative model (Greve et al., 2022). Studies were also carried out to determine which impact chains occur directly after the implementation of a modular structure and which become relevant after a delay (Greve et al., 2021).

3 Research Gap and own Preliminary Work

In summary, it can be said that there are many methods for the development of modular product families in the literature, which raises the question of whether there is a need for further methods in this area or whether existing methods already implicitly address future issues. It can also be seen that at first glance, some of the existing methods are closely linked to each other and differences between the methods are not so easy to detect. The methods are described very differently in the literature, some publications are rather frameworks (Jiao and Tseng, 1999), in others a step-by-step procedure is presented in text form (Kusiak, A. and Huang, C; Pimmler and Eppinger, 1994). Method visualizations with explanatory illustrations are also included in some method descriptions (Forti et al., 2023; Pakkanen, 2015). There is no uniform form of description of methods for the development of modular product families and their module-building steps. The documentation on the methods sometimes refers to economic targets. For example, Erixon describes that the use of its module driver "carryover" can deliver cost benefits as the development effort is lower (Erixon, 1998). Pimmler and Eppinger state that product architectures developed using their method bring about an improvement in quality (Pimmler and Eppinger, 1994). Impacts of modularization can not to be found in the method descriptions.

Several comparisons of methods can be found in the literature. Daniilidis, for example, has developed a framework with which methods for the development of modular product families can be compared in terms of addressing product variance, product lifecycle and product generation considerations (Daniilidis et al., 2011). Criteria such as repeatability and suitable application areas are also used to compare methods, for example by Hölltä (Hölttä, 2004). Although the method comparisons show differences between different methods for the development of modular product families, the comparison criteria do not address the different impacts the methods have on economic targets.

In our own preliminary work, module-forming steps of methods for the development of modular product families were described in a standardized manner. These steps were then linked to the IMF. This made it possible to show which methods for developing modular product families can address which impacts of modularization (Figure 2). The link was made via the module drivers that are used in the methods for developing modular product families for module formation.

The module drivers can be linked to the properties, to individual impact chains or even to entire life phases. This depends on the respective level of detail.

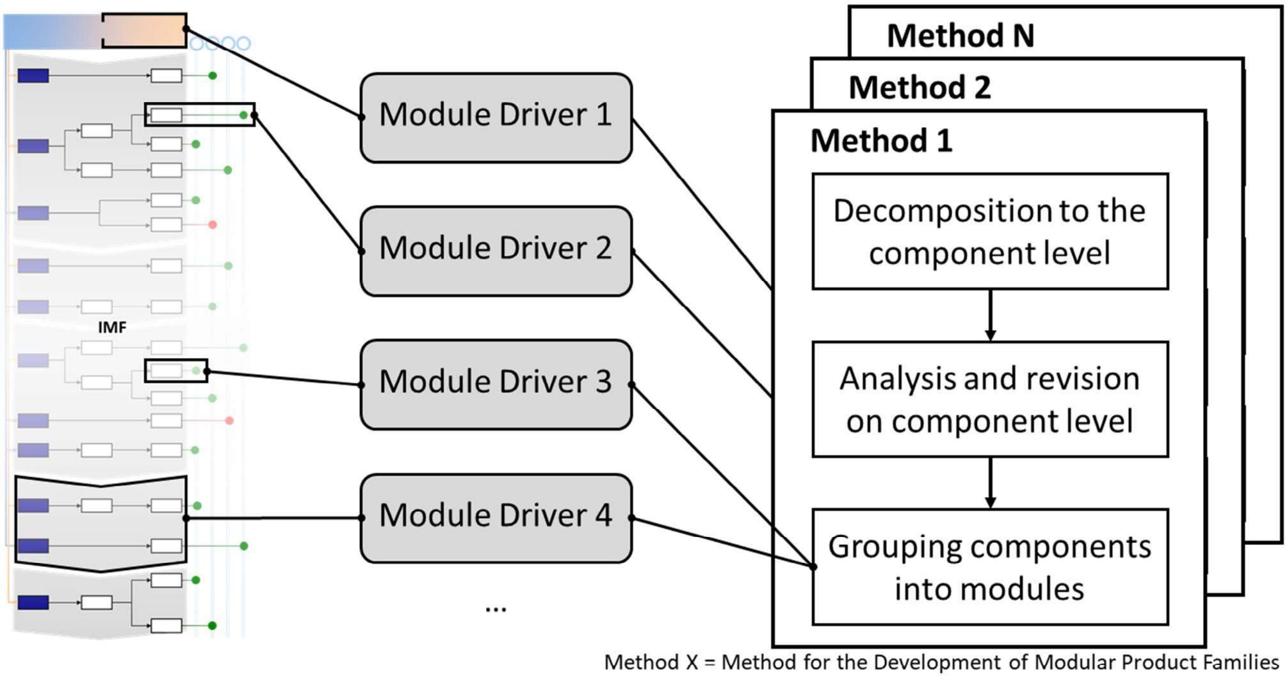

Figure 2: Linking methods for developing modular product families to the IMF

In this paper, the following research questions will be addressed on this basis: How can the selection for a method to develop modular product families be supported based on addressing economic goals? How can existing methods of modular product families be adapted to desired economic goals?

4 Methodical Support for Method Selection and Adaptation

In order to answer the research questions posed in Section 3, the following methodical approach to method selection and adaptation is presented in this paper. This approach consists of four phases.

Phase 1: Recording the Company's Objectives

In order to be able to select a method for developing modular product families in a target-oriented manner, company-specific objectives must first be defined or included. For this purpose, the initially generic IMF can be used in different ways. The IMF is used because it allows companies to sharpen their objectives.

As the IMF contains different life phases, the objective can also be defined by several departments within a company. A common objective in which everyone agrees also promotes cooperation in an upcoming modularization project. The aim of this phase is to define relevant impact chains from the IMF (Figure 3).

The way in which the objectives are recorded is workshop-based and cross-departmental. There are different options depending on the time frame. First, all workshop participants are given an introduction to the topic of the impacts of modular product families. The causal relationships of the individual impact chains are then presented. This is followed by the selection of company-specific impact chains. If basic knowledge in this area exists, this can be worked on directly in the IMF. If the many contents in the IMF are more likely to be overwhelming, questionnaires can be used in which the causal relationships of the impact chains are implicitly queried, thus enabling a certain degree of accessibility.

As already mentioned in the state of the art, the IMF is repeatedly used in research projects with companies. This results in a database on the impacts of modularization, which can be filtered on the basis of company boundary conditions. This database can also be consulted when defining the objectives of a new company. After the first impact chains have been selected, this selection is compared with entries from companies in the database that have the same or similar company boundary conditions. The comparison provides a basis for discussion and makes it possible to consolidate the objective. If it becomes apparent during the discussion that some impact chains of the company-specific IMF are more important to the company than others, this should also be noted in the company-specific IMF.

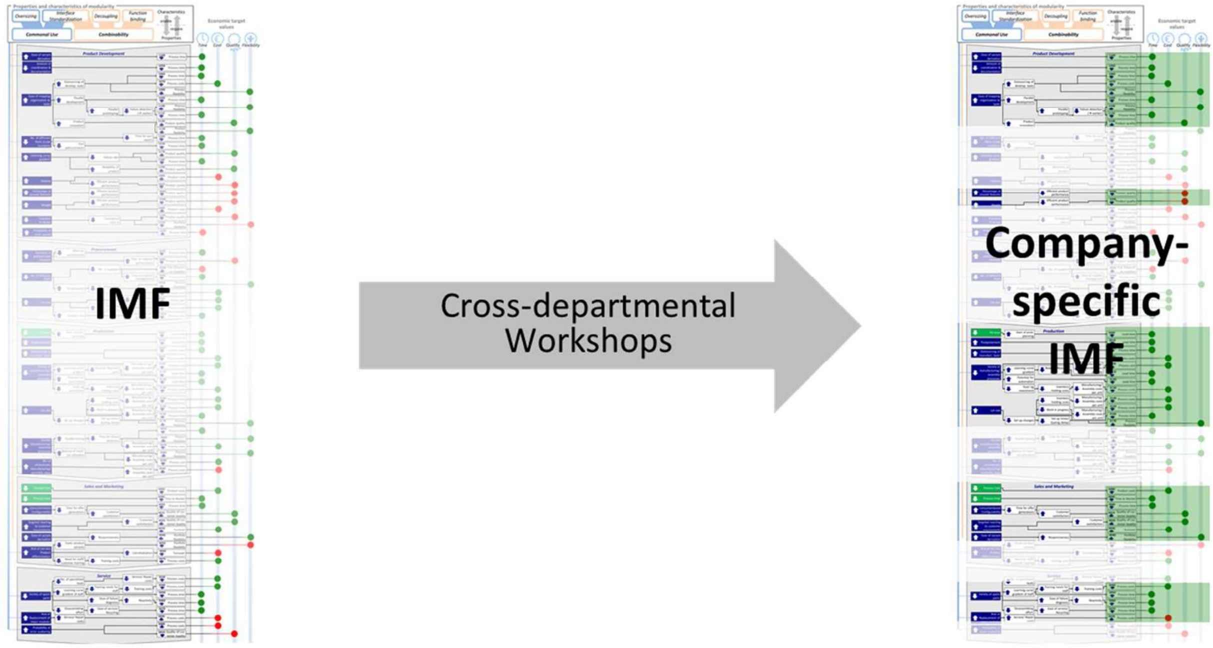

Figure 3: Derivation of a company specific IMF

Phase 2: Analysis and Identification of Module Drivers and Methods for the Development of Modular Product Families from the Methodstep-database

After defining the objective by creating a company-internal IMF, this information is used to filter the methodstep-database, which was developed in (Schwede et al., 2022) and briefly described in Section 3, for suitable module drivers. For this purpose, the methodstep-database is examined for links to module-forming steps for the individual selected impact chains. It should be noted that the term "module driver" refers not only to the set of module drivers from Erixon, but also to module forming reasons in general, which are specified in the various methods.

If the objective had now resulted in the selection of, among others, impact chains No.1090 and No.5070 (Figure 1) in Phase 1 of the methodical procedure, this would look as in Figure 4. According to the methodstep-database presented in Schwede et al., the impact chain No. 1090 is addressed by technically functional module drivers or the module drivers "functional aspects" (Schwede et al., 2022). As these module drivers address all impact chains that occur due to combinability in the product development life phase, the link is made indirectly via the product development life phase. These module drivers state that components that together fulfill a certain product function should be combined into a module. Impact chain No. 5070 is directly addressed by several module drivers according to Schwede et al (Schwede et al., 2022): Recycling (material, thermal, product), disposal, maintenance, upgrading and service. On the one hand, these reasons state that components should be combined into modules in such a way that they can be recycled module by module. On the other hand, when creating modules, care should be taken to ensure that components that are likely to be upgraded together or require service are combined into one module. Such analyses of the methodstep-database are now carried out for all impact chains selected in phase 1. The methods for developing modular product families are then additionally analyzed to determine the module-driving reasons that represent the link between the impact and the methods. The impact chain No. 1090 can be addressed using technical-functional module drivers, which can be found, for example, in the methods from Blees (Blees et al., 2010), Blackenfelt (Blackenfelt, 2001) or Pimmler and Eppinger (Pimmler and Eppinger, 1994). Impact chain No. 5070 is addressed by methods such as from Blees (Blees et al., 2010), Erixon (Erixon, 1998) or Kobayashi (Kobayashi, 2001).

Phase 3: Selection of Methods for the Development of Modular Product Families

The methodstep-database analyses described in phase 2 are now carried out for all the impact chains selected in phase 1. Based on the analyses, a method selection can now be made. If there is a method that addresses all the impact chains selected in phase 1 through its module drivers, this can be selected directly. If this is not the case, methods that address some of the impact chains can be expanded to include the module drivers that address the other impact chains.

In our fictitious example, either the integrated PKT approach could be selected or, for example, the module-forming step of the DSM method according to Pimmler and Eppinger could be extended to include the module drivers recycling, service and upgrading. By describing the module drivers in the database using a standardized method step description, it is now possible to estimate which method or which method adaptation is feasible in the company. At this point, factors such as previous experience with individual methods and the amount of work involved play a role.

If the effort involved is not too high, modularization using both methods is also advisable. If the modularization concepts differ, they can then be compared with the help of the IMF.

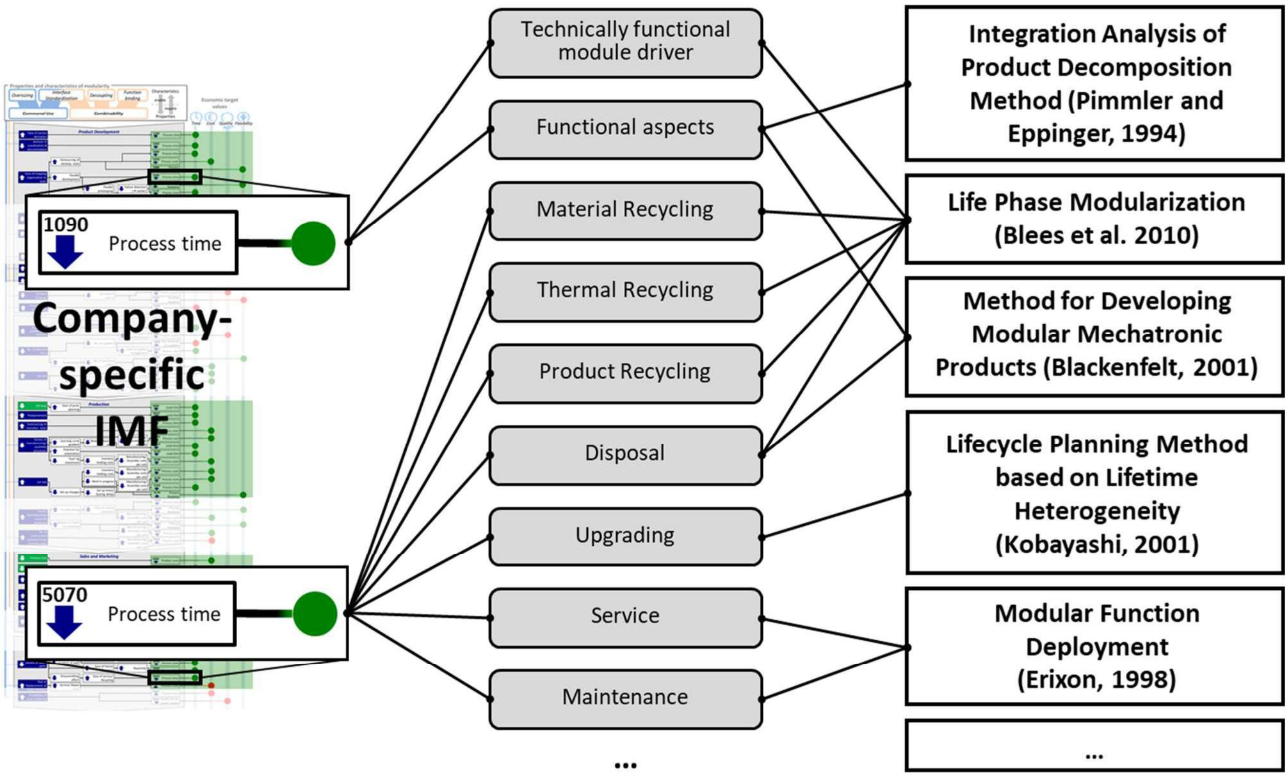

Figure 4: Identification of Module Drivers and Methods for the Development of Modular Product Families

Phase 4: Prioritization of the Module Drivers and Concept Selection

In the methods for developing modular product families, module drivers are mentioned which can be used to form modules. However, these module drivers can also be contradictory. For example, a module that was formed for technical-functional reasons (reference to impact chain No.1090) may contain components that cannot be recycled together (reference to impact chain No.5070). In such situations, the prioritization in the company-specific IMFs indicates which module drivers are to be given priority when forming the module.

However, it should be noted that the same modular product architecture does not necessarily apply across all life phases. For example, a product development module can be procured together with another module, whereby the product development module is extended from the procurement perspective. From the production perspective, the module definition may look different again. It is important that the different views of the life phases are harmonized.

If several methods were selected in Phase 3 and subsequently applied, the IMF can also be used to compare concepts of modular product families. The database for calculating the economic target values can be used. This database is literature-based, as the authors have found that each company has different access to its data and also calculates key figures differently. Together with the company for which a final method selection is to take place, the key figures for both concepts are calculated for the company-specific IMF and compared with each other to support the concept selection.

5 Discussion

By linking methods for developing modular product families and the IMF, a selection of methods based on addressing economic targets can be made, which answers the first research question. The second research question can be answered by selecting or prioritizing module drivers based on it.

In Chapter 4, a procedure was presented that is intended to support companies and management consultants in selecting a suitable method for developing modular product families for an upcoming modularization project. This selection should be based on the economic objectives of the company. Individual phases of this procedure have already been tested in various research projects and also with the help of an experimental study.

The IMF was used in various project-related workshops to present company-specific objectives. Different approaches have been tested in recent years. It turned out that a detailed explanation of the impact chains is important and that these are not self-evident to all outsiders. In some cases, it was also necessary to simplify the relationships. The comparison of the pre-selected impact chains with the existing database on impacts also proved to be very helpful in the final selection of impact chains.

In the course of selecting impact chains, new impact chains and even new life phases emerge from time to time. For example, the IMF was used in a company from the aviation industry. The aftersales life phase was included in the IMF on a company-specific basis. This also included some new impact chains that deal with retrofitting. When applied in another company from the construction industry, the IMF was expanded to include the target size of sustainability. In other applications, the topic of complexity costs was discussed in detail in the course of creating the company-specific IMF.

The selection of methods for developing modular product families represents the core of the approach presented in this paper. The application and use of the database were tested in an experiment with students. Four groups of 6 Master's students each received an example company and its economic objectives as interview excerpts. Based on this, they were each asked to decide on a method for developing modular product families for the company using the database. Three of the four groups opted for the method that was directly addressed in the methodstep-database via the specified economic objective. One group should actually have chosen a method for the development of modular product families with a focus on sustainability based on the specified objective, but opted for Erixon's Modular Function Deployment (Erixon, 1998) on the grounds that this method is more comprehensive. As this method also includes sustainability aspects, this choice was not wrong.

The methodstep-database was also used in research projects after different company-specific IMF were created. It turned out that at least the companies we worked with were already committed to certain method for the development of modular product families or had established their own approach to modularization within the company over many years. Nevertheless, it was very helpful to identify the reasons for modularization that should be used to achieve the set economic goals. These module drivers should be included in the existing procedures for future modularization projects if the economic objectives remain the same. Furthermore, it was recognized that the IMF and the methodstep-database can be used to demonstrate the strengths of the methods currently used to develop modular product families.

6 Outlook

The IMF is generally based on a generic structure, which is why company-specific adjustments to the IMF that are made in industry projects are not transferred to the generic IMF. Necessary adjustments are always made on a company-specific basis. Due to the ever-increasing relevance of the topic of sustainability for manufacturing companies, it is desirable to integrate the target variable of sustainability into the IMF. To this end, specific literature research and analyses of the impacts of modular architectures on sustainability target factors must be carried out. Based on these analyses, the generic IMF should be expanded to include sustainability as a target variable.

From an economic perspective, variant-induced complexity costs are becoming increasingly relevant for companies. As variant-induced complexity costs can be positively influenced by modular product architectures, it makes sense to integrate the target variable of complexity costs into the IMF in order to be able to identify the impacts of modular design decisions on complexity costs at an early stage. Initial studies have already shown that complexity costs are implicitly taken into account in the IMF. In order to show concrete connections between the development of modular product architectures and the influence on variant-induced complexity costs and to be able to apply them in practice, these investigations should be deepened and concretized in subsequent research.

The possible integration of the above-mentioned target variables in subsequent research can enable the target-size-oriented development of modular product families with regard to eco-efficient product architectures.

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