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Long-term effects of modular product architectures: An empirical follow-up study

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Abstract

The use of modular product architectures gives rise to a variety of effects in all areas of the company. So far, the effects that occur after a short period of time have been investigated - the effects that arise only after a certain period of time or a certain proportion of modules used are often neglected. The latter can, however, have a major influence on the economic targets, but are usually not taken into account in the initial modularization, since they are not known or can only be addressed imprecisely. For this reason, an empirical study will be conducted in this paper to expose the long-term effects of modularization. A model for the identification of time-dependent effects will be developed and applied to an example of a medium-sized elevator manufacturer. The result of this work is the derivation of success factors for the implementation of modular product architectures on the basis of long-term success.

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Keywords: modularization; product architecture; long-term effects; empirical case study

1. Introduction

In mechanical and plant engineering, the development of modular product architectures (mPA) is increasingly being used to meet the market's growing demand for individualized products while at the same time mastering internal product and process variance. The effects of those product structuring measures occur in many processes along the entire value chain of a company, are often very in-transparent and difficult to comprehend [1]. In addition, many of the effects only occur after a certain time (e.g. by exploiting synergies) and under certain conditions (e.g. by a certain module share in the overall product range), so that these are often not taken into account in the initial development of the mPA. The literature contains various studies that examine the general effects of mPA, but often insufficiently analyze the extent to which the effect is time-dependent. The studies are also carried out either directly after the initial modularization (only short-term effects can be measured) or after a certain time interval - but without taking into account possible influencing factors that are not or only indirectly connected with the modularization (e.g. sales fluctuations). Both circumstances lead to a distortion of the real effects and, thus, to a wrong target image in the development of mPA. The aim of this paper is to identify the long-term and immediate effects of modularization by means of a follow-up study.

Specifically, two research questions are to be answered in this thesis:

Q1: How can long-term effects of modular product architectures be methodically incorporated?

Q2: What long-term effects have modularization measures had and which success factors can be derived?

To answer these questions, existing effects from the literature are identified and a model for carrying out the follow-up study is developed. The model is applied to the example of a medium-sized elevator manufacturer in which the development and introduction of mPA has been directly

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accompanied for over 5 years in a cooperation project. Both quantitative and qualitative data from all areas of the company are collected and compared with the data prior to modularization. The result of this work is the derivation of possible success factors for the implementation of mPA on the basis of long-term success.

2. Literature review: Effects of modular product architectures

In the context of product development, the product architecture can be described as the assignment of the functions to the building blocks of the product and the specification of the interfaces between interacting physical components [2]. A modular structure of a product architecture offers the possibility to maintain a high external product diversity and to reduce the internal diversity within the company. This enables the associated complexity of business processes in product development to be mastered, reduced or avoided [3]. The concept of modularity can be understood as a gradual entity of a system of products and not of a single product and is characterized by five basic properties according to [4], namely commonality (use of components or modules in several products), combinability (use of modules to configure the product variants), functional binding (1:1 or n:1 assignment between functions and modules), interface standardization (physical standardization of interfaces of modules) and decoupling (interaction and binding between modules is weaker than the internal coupling of module components). These properties are themselves gradual parameters and in their totality determine the overall degree of modularity. When developing a mPA, there is no ideal value for a degree of modularity that points to an optimal architectural design - it is rather the degree to which an optimal compromise between advantages and disadvantages is sought in the context of the needs of all relevant stakeholders (designer, manufacturer, customer, etc.) [3].

In order to make targeted use of potential within the framework of product structuring measures, the effects of mPA must be known along the life cycle phases. There are studies on these both from the area of the product development research, and from the economic area of management consultancies.

In [5] the performance effects that can be expected from increasing the modularity of a company's product portfolio are investigated. As a result, the positive effects of modularity on the success of the company are confirmed. A reduction in procurement costs and lead times was observed in connection with a high modularity of the product portfolio. On a sample of 115 companies from the electronics industry the influence of product modularity on innovation strength and the success of new products is surveyed. The authors come to the conclusion that innovation strength plays a mediating role between modularity and the success of new products, but does not directly influence them [6]. [7] examine the impact of mPA (especially product platforms) in the literature and analyse the content of 66 scientific papers. They determine 27 different product platform effects, which are mentioned differently frequently. The largest part of the effects researched is derived from chains of arguments, only a smaller part is described on the basis of concrete application cases. [8] investigate the relationship between modularity and cost of a product over the life cycle phases. A significant relationship between the modularity of a product and life cycle costs cannot be statistically demonstrated in this case as long as the changes in modularity are not sufficiently large. Furthermore, they put forward the thesis that cost reductions are to be expected especially at the beginning of modularization measures, a long-term consideration is not carried out here either. [9] concentrate on the immediacy of effects and expose direct and mediated ones mainly on development time and product performance.

Based on a broad literature review, reference [10] provide a comprehensive model of the relationships between modular properties and economic, life-phase-dependent effects with the Modular Product Family Structure Impact Model. The model offers a very up-to-date summary of the findings from the literature and shows the relationships between the effects, but also neglects time dependencies.

Previous studies on the effects of mPAs were mostly carried out selectively (one-time recording of the effects in a company at a time) and neglect a temporal dependency of the effects. In order to be able to investigate these aspects as well, a methodical approach for conducting long-term studies in the field of product development research will be introduced in the following, which will then be applied to the case study of an elevator manufacturer.

3. Procedure to determine long-term effects of mPA

A possibility to investigate long-term effects is offered by longitudinal studies (also called long-term or longitudinal studies) in which one or more variables are studied over a longer period of time or in follow-up studies at several points in time. Such long-term studies have so far been little used in product development research [11].

In order to determine the time-dependent effects of mPA, not just the development and implementation phase of the modularization but also the care phase must be taken into account [12]. Figure 1 shows the phase model with the required data and the corresponding effect types.

At the initial point before the modularization, the data to which reference is made later needs to be recorded. Here, the aspects that represent the reasons for the development and introduction of mPA are to be captured above all. In the subsequent development phase, only minor effects are to be expected, so that only the applied modularization measures can be observed here. In the implementation phase, the first effects become clear, which will be referred to below as short- or medium-term.

Long-term effects mainly arise in the care phase, as the mPA is implemented throughout. An alignment of the effects from the implementation phase reveals the effects that only occur after a certain time or with a certain proportion of

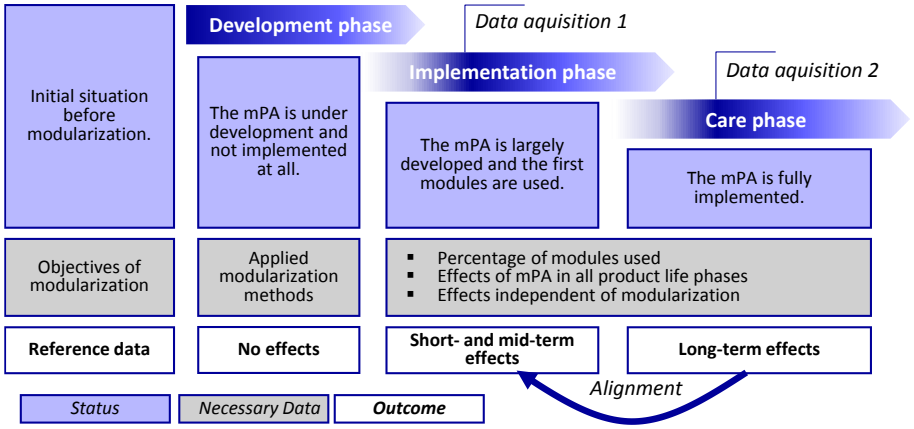

Fig. 1. Phases of a modularization process with necessary data to gain corresponding effects

modules used. Since the start time of the care phase is not necessarily clearly defined and depends on the life span of the product, a sufficiently long period should be chosen after implementation.

In general, it is important to ensure that the same study design is used when recording data at different points in time. In order to also filter out the effects that are independent of modularization (e.g. through general process improvements, new machines, etc.), a comparative analysis of assemblies that have not been modularized must be carried out. A suitable reference product architecture must be selected and it must be determined which changes have resulted from other measures in addition to product structuring. For the recording of the data in the respective phases quantitative as well as qualitative recording techniques are required, which should be chosen depending on the availability.

4. Application to a casy study

The procedure presented was applied to an elevator manufacturer in special plant engineering. The examined company is a medium-sized enterprise with approx. 220 employees, which was accompanied over the entire period under consideration and methodically supported since the initial modularization. This ensures that data is available at all times and that the product structuring measures carried out are known.

4.1 Study design and execution

The total observation period of the case study is 5 years, the data acquisition took place at t_1=2.5 and t_2=5 years. Both qualitative and quantitative recording techniques were used to record the required data. Since many of the effects of modularization are to be expected in quantities that cannot be measured directly (e.g. transparency), the results of interview studies serve as the core data basis. At both times a total of 21 employees from the management and departmental level along the entire value chain were interviewed. At t_1 the agreement to the occurrence of the effects and at t_2 their development since t_1 was queried. For this purpose, the impact model of [10] was used and the effects contained therein were queried and supplemented. The most relevant assessments were evaluated in terms of their occurrence by the experts. In order to increase the validity of the data evaluation, care was taken to ensure that the same interview partners were always interviewed at both times, or at least have the same positions in the company. Quantitative data were mainly collected to determine the proportion of modules used. In addition, measurable effects, such as process times in development and production, were checked by means of quantitative data evaluation. To determine the effects that are independent of the modularization measures carried out, the assemblies that are not covered by the mPA were used.

4.2 Results

At the outset, the modularity of the existing product architecture is limited to the functional binding of subassemblies, which brings advantages in the development department for forming organizational units, but leads to major problems in other departments (high engineering effort, long lead times, high error rate in production, problems in assembly). In the development phase, the product architecture of the elevator was clustered into main modules, which were sequentially modularized according to technical-functional as well as product-strategic aspects using the methods of the Integrated PKT Approach for the development of modular product families [13]. The structure of the basic modularized elevator can be seen in Fig. 2.

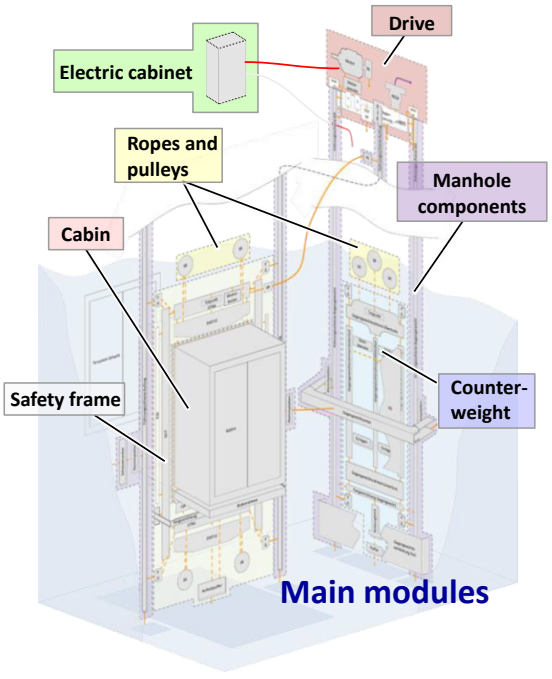

Fig. 2. Overview of the developed main modules of the elevator [13]

For the individual main modules, the product architecture was sequentially modularized and a self-contained mPA with defined interfaces to other main modules was developed. For this purpose, parametric CAD models were created in order to increase the configurability in development and still cover a high proportion of external diversity. Once a main module has been modularized, it is released and can be used. This represents the transition to the implementation phase.

For the application case, the use of four main modules (for reasons of secrecy called MM 1-4) was analysed over the observation period in order to obtain more valid statements through a broader database. The frequency of use of the main modules covered by the mPA is plotted as a function of time in Fig. 3.

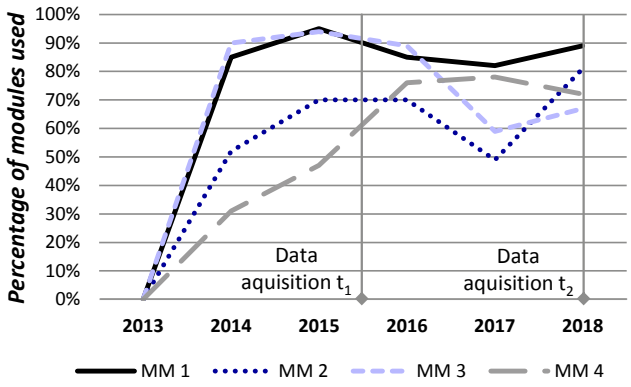

Fig. 3. Time course of the use of the modularized main modules (MM)

In 2015, for example, 70% of all MM2 requests were covered with components from the configurable mPA. The remaining 30% required an adaptation or special design of this assembly. At the time of data acquisition t_1 all considered main modules are in the implementation phase. Approximately 2.5 years after introduction, an average of approx. 80% of all inquiries can be covered here. At the time of the second data acquisition, the average module share is similarly high, with a drop in the frequency of use between data acquisition t_1 and t_2. MM2 and MM3 are particularly affected here. Inquiries revealed that at this point in time changes to the product architecture were necessary. The reason for this was the lack of conformity of the required specifications with those covered in the mPA. The two main modules were successfully adapted so that the following year again saw a higher frequency of use. The consideration of future requirements is therefore an important aspect of modular development in order to meet changing requirements. Even if the transition from implementation phase to care phase cannot be clearly determined, these revisions of the product architecture can indicate the entry into the care phase.

At t_1 and t_2, interview studies on the effects of the mPA were carried out in the individual departments. At t_1, the assessment of the initial situation was asked and at t_2 the development of the effect since t_1. The average results for the four main modules are presented in Table 1. The tendency is coded in the representation by means of a symbolism (arrow) and the effects are sorted in the individual phases of life in descending order according to their long-term occurrence.

Table 1. Short and long-term effects in the life phases determined from the interview studies

Life phase	Effect	Short-term (t_1)	Long-term (t_2)
Sales	Easier price calculation	○	↑ ◕
	Improved customer satisfaction	○	↗ ◑
	Improved configurability	◔	→ ◔
	Improved acquisition of new customers	○	→ ○
	Poorer product differentiation	◕	↘ ◔
Development	Reduced documentation effort	○	↑ ◕
	Reduced design times	●	↗ ●
	Reduced planning variances	◑	↗ ●
	Better parallelization of the design work	◑	↗ ◕
	Simpler implementation of new processes	○	↗ ◕
	Reduction of the variety of components	◕	→ ●
	Reduction of development costs	◕	→ ◕
	Less design freedom	◑	→ ◑
	Oversizing of the components	◕	↘ ◔
	Increased need for employee trainings	●	↓ ◔
Procure-ment	Improved plannability	◔	↗ ◑
	Improved procurement conditions	◑	→ ◑
	Reduction of the number of suppliers	◔	→ ◔
	Reduction of the number of order transactions	○	→ ○
Production	Improvement of production planning and control	◕	↑ ●
	Reduction of errors	◕	↑ ●
	Increased production flexibility	○	↗ ◑
	Reduction of production times	●	→ ●
	Reduction of production costs	●	→ ●
	Reduction of production variance	○	→ ◔
	Reduction of tool costs	◔	→ ◔
After-Sales	Easier maintenance	○	→ ○
	Reduction of the number of stock items	○	→ ○

Consent to the occurrence of the effect

- ● fully agree
- ◕ rather agree
- ◑ partly agree
- ◔ don´t agree much
- ○ disagree

Occurrence of the effect in comparison to t_1

- ↑ much stronger
- ↗ rather stronger
- → similar
- ↘ rather weaker
- ↓ much weaker

Basically, it can be said that the short-term effects are most significant in development and production. High economies of scale can already be achieved in the early implementation phase due to reusable templates and standardized processes. These effects are dependent in their temporal course on the proportion of modules used. In concrete terms, the reduction of construction and production times can be mentioned in this context. This statement could be confirmed by a statistical evaluation of quantitative data at t_2. The development and production times of overall 54 MM1 (31 with mPA; 23 without mPA) were recorded and compared. By using a MM1 with mPA, it was possible to save about three times the time (design) and twice the time (production) in comparison to a MM1 without mPA (see Fig. 4). The standard deviation of the two parameters was also significantly lower when using the

mPA, which in turn has a positive effect on the plannability of the activities.

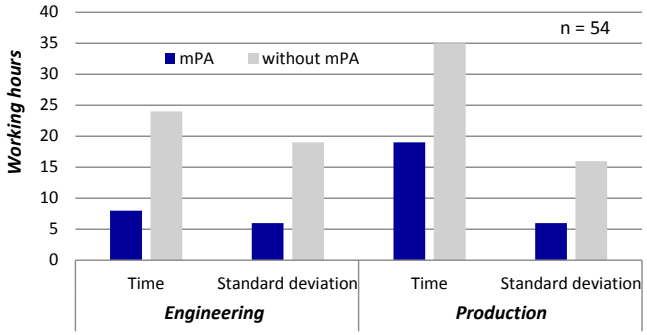

Fig. 4. Comparison of working time for MM1 from design and production when using mPA

In sales, purchasing and after-sales, the short-term effects are rather less significant. The reasons given for this are the lack of documentation of the modules and the low involvement of employees from these product life phases.

If one now considers the temporal development of the effects, it becomes apparent that not only effects in the operative area (e.g. reduction of construction and production times), but also overarching effects and cross-sectional aspects come to the fore. Here, the simpler price calculation in sales or the smaller deviation of planning variants in design and production can be mentioned above all. Although the frequency of use of the modules does not change significantly, there are benefits from consistent documentation of the module specifications as well as defined application areas and limits in these areas. This increases transparency, which in turn leads to lower expenses for employee training. In addition, the planned times of the new mPA can be adjusted by increasing the number of available samples.

Further long-term effects are attributable to process adjustments that are not directly related to modularization but are favoured by it. Here, for example, the conversion from welded constructions to edged laser parts can be mentioned, which has an effect on throughput times in production, but has also been facilitated by the new modular design. Furthermore, the revision of processes within the framework of modularization has revealed the potential of targeted process design and has led to processes beyond product architecture design being critically scrutinized and improved, which has an indirect effect on the economic target values. Thanks to an established feedback process, production also has the opportunity to influence designs quickly and sustainably. The possibility of reporting errors and influencing the designs (for example with regard to assembly) increases productivity in production on the one hand and the motivation of employees on the other, as suggestions for improvement are now better taken into account. This feedback process was made possible by the precise documentation of the mPA of the individual main modules.

Effects in the after-sales area could not be identified at either time. The reason for this may be that the effects only occur after a certain stage in the life of a product. For example, a reduction in the dismantling effort, a reduction in the time required for maintenance activities or their simplification and simpler fault diagnoses can only be determined after a certain period of time. In this case, the time aspect was too short, since the product lifecycles of elevators are about 20-30 years.

4.4 Key findings

After the evaluation of the study, the following success factors can be derived for sustainable modularization.

Cross-departmental implementation: To achieve effects along the entire value chain, the various departments must not only be involved in the initial design of the mPA, but also in its implementation. In the application case, a correlation between the degree of implementation and the occurrence of effects could be demonstrated. At t_2, the interview partners were asked qualitatively about the degree of implementation and the results were plotted with the average occurrence of the effects (see Fig. 5).

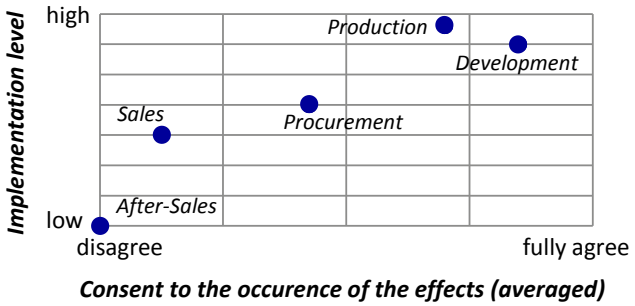

Fig. 5. Qualitative dependence between degree of implementation and occurrence of long-term effects in individual departments

It can be seen that the departments with the most long-term effects also highly rated the degree of implementation of the mPA.

Consistent specification and documentation: The application areas and functional scope of the various modules must be clearly defined and documented so that they can also be used profitably in those phases which are not directly involved in the creation (sales, purchasing, after-sales). Particularly when selling configurable modules, precise knowledge of the limits is important so that more expensive special designs are not sold and calculated as modular configurations.

Continuous care: To be efficient in the long term, an initial designed mPA must be continuously maintained and adapted to changing requirements by both external and internal stakeholders. Here it makes sense to define responsibilities and anchor them in the organization (e.g. in the form of a module manager).

Early consideration of future requirements: In order to reduce the maintenance effort in advance, future changes can already be anticipated during the initial creation of the mPA (f.e. by forecast methods) and taken into account by a future robust product architecture design.

Parallel adjustment of processes: Since the greatest effects of mPA are mainly in the processes, they must be adapted to the new product architecture. The case examined showed that both the design of the product architecture itself and the design of the processes play a decisive role in the successful implementation of product structuring measures.

6. Discussion

By conducting the follow-up study, the effects of mPA could not only be identified, but also placed in a temporal context. The effects determined in this application case must always be seen in relation to the product (scope, complexity, service life, number of units, etc.) as well as to the company (size, experience, type of value chain, etc.). In addition, the focus of the initial modularization is always decisive for the development of individual effects. In the present case, the greatest effects (short- and long-term) can be seen above all in design and production. This can be attributed on the one hand to the defined objectives of the modularization project, but also to the chronological order of implementation in the value chain of the company. No effects could be identified in after-sales, which can be attributed to the lack of inclusion as well as to the time lag to the development. A further data acquisition should be carried out at a later point in time in order to identify the effects in this late phase of product life.

With regard to data acquisition and evaluation at the respective points in time, extensive statistical evaluation was difficult, especially in the qualitative study, because the sample was too small. Thus, this work was limited to qualitative evaluations, which, however, can be classified as sufficiently accurate by the selection of the interview partners (managing directors, all department heads and various employees) and the clear tendencies of the answers. The results can therefore be regarded as valid. The quantitative results obtained, on the other hand, can be evaluated as very accurate, as the number of samples was relatively high in addition to the measurement method.

The derived success factors are estimated to be largely independent of the boundary conditions. For verification purposes, the study design presented should also be transferred to other applications and the results should be compared with each other.

7. Conclusion and outlook

In this paper, a follow-up study was conducted to assess the effects of mPA in a company. First, a phase model for categorising and recording the effects was presented and applied to a case study of a medium-sized elevator manufacturer. At two different points in time (intervals of 2.5 years each), the effects in the individual departments were qualitatively recorded by means of an interview study and compared with each other. This comparison allowed a statement to be made on the effects which occur only after a certain period of time since the introduction and at a certain frequency of use of the mPA. In addition, some effects were confirmed by the evaluation of quantitative data. From the findings of the study, case-independent success factors were derived which should be taken into account in sustainable modularization.

In particular, the success factor of early consideration of future requirement changes is of great interest, as this represents a preventive measure and reduces costly changes to the product architecture later on. The research on the development of such future robust product architectures is therefore of great importance for further work.

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