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TOWARDS AN IMPACT MODEL OF MODULAR PRODUCT STRUCTURES

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Abstract

Modularization of product families affects firms in many ways. Many of them have been investigated in research and observed in industry. But which effect will most likely occur, by which kind of modular product structure it can be achieved and how this product structure affects other life phases is often not clear because the understanding for the whole system of product structures and effects is missing. The aim of this paper is to show the interrelations between product structures and the effects they entail. Hence it provides the desired system view. For the model development the properties and characteristics are defined to be able to differentiate product family structures. For collection of the effects a literature study was undertaken, the effects and their product structural causes are investigated and displayed in a flow chart based visualization, which is divided into product life phases. The value of the paper lies in the provision of a visual model including product structural cause and its life phase effects on a firm which has been missing in literature and is important for decision-making.

Keywords: Product families, Product structuring, Design process, Modularization, Impact model

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1 INTRODUCTION

Modular product structures have wide-reaching impact on production companies. Product development not only significantly affects the cost of subsequent life phases (Ehrlenspiel and Meerkamm, 2013), but is also largely responsible for quality and lead time of a product. Creation and handling of diverse product variants also occurs in development and production of product families. Modularization makes it possible to decrease internal variety. It acts on areas of product life phases in different ways, but the overall relations cannot be overlooked. Pinpointing the relations supports decision-making when modularizing product families. It is therefore important to know and understand the relations between the product structure of a variety afflicted product family, being determined in product development, and the effects that the relations have on subsequent life phases. The impact model of modular product structures begins at this point and is an explanatory model that shows the effects and relations that modular product structures can have within companies. This paper describes the current impact model and outlines future developments. Two case studies are presented to explain the relevance of boundary conditions to the occurrence of the effects. Research questions are provided in Section 2. Findings are related to current research and are presented in Section 3. The end of Section 3 shows an example of the impact model then the company reference is established in Section 4. Section 5 closes with a discussion of the model and proposed further developments.

2 OBJECTIVE OF THE IMPACT MODEL

Modularity has many effects; it is easy to lose track of the impacts that it has on different areas of a company. To simplify and track the impacts, a model that displays the relations is provided in this paper. Research questions (RQ) are developed to assist in the creation of the model. One of the main questions is about what can be achieved with modularization. The research question is:

1. Which effects entail modularization in a company?

Modularity, as a gradual entity (Krause and Eilmus, 2011), can be increased by defining different product structures. This leads to a second question:

2. Strengthening which properties of modularity triggers which effects?

The economic value of modularization leads to the third question:

3. In which way do these effects economically affect a company?

The results of the ongoing research on these questions are given in Section 3. An initial impact model was previously introduced in Hackl and Krause (2016). It consists of three parts, which are shown in Figure 1.

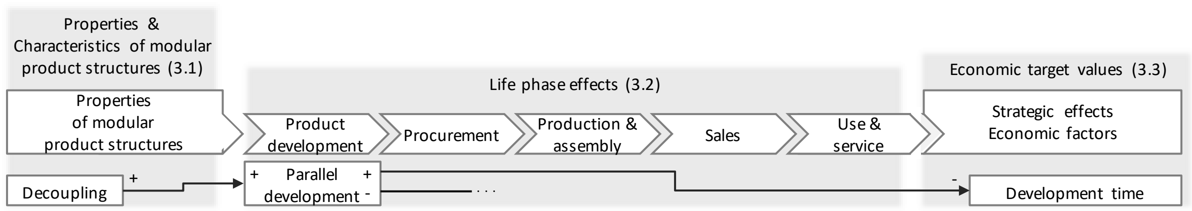

Figure 1: Structure of the impact model (Hackl and Krause, 2016)

The first part (Figure 1, left) displays the properties of modular product family structures. It mainly contributes to RQ2. The second part (Figure 1, middle) shows which effects occur in the life phases of the product development process (RQ1). The third part concentrates on economic factors that sum up the life phase effects and their economic outcomes (RQ3). This paper aims to enhance the existing model with further specification to more precisely contribute to the research questions.

3 ENHANCEMENT OF THE IMPACT MODEL

The literature study by (Hackl and Krause, 2016) showed that many papers exist, naming and investigating individual effects of modular product structures. For example, Ulrich (1994) gives an overview of the benefits and drawbacks of modularity; and Sheu and Wacker (1997) investigate the effect of purchased part commonality on manufacturing lead time. Some impact models already exist, however they concentrate on either properties (giving effects which are triggered by a specific modular product structure (Boer, 2014; Fixson, 2006)) or the contribution of modularity to economic value (Harland and Uddin, 2014; Lau Antonio *et al.*, 2007; Danese and Filippini, 2013; Gualandris and Kalchschmidt, 2013; Sohail and Al-Shuridah, 2015; Worren *et al.*, 2002). They do not specify which types of modular product structures lead to certain life phase and economic effects, so the fundamental context is not fully apparent. In the following three subsections, each of the three main impact model parts will be put in context with the state of science and enhancements will be displayed. Section 3.4 shows the current impact model of modular product structures.

3.1 Properties and characteristics of modular product structures

Knowing how to differentiate modular product structures is necessary to contribute to RQ2. Different product structures have different consequences in a company. Therefore, this difference in product family structures must be describable. Differentiation to date has been based on Salvador's set of definitional perspectives on modularization, which has been researched in a literature analysis. According to Salvador (2007), product modularity is defined by:

- Component separability
- Component combinability (being supported by)
    - Functional binding
    - Interface standardization
- Component commonality

To enhance this differentiation, adapting Weber's definition of properties and characteristics is useful when defining a set that describes the difference between product structures. Weber (2007) defines properties as describing the behaviour of a product that cannot be influenced directly by the designer. They can be understood more as an outcome of characteristics. Characteristics, in contrast, describe the structure of products that can be influenced by the designer. Product structure properties require particular values of characteristics to be able to behave in a certain way, whilst characteristics enable properties to behave as desired. Weber's definition of properties and characteristics is adapted for the impact model. Characteristics now specify technical details of *single modules*, which are enable properties to support modularity (Figure 2, right). Properties describe the *interaction of modules* in a product family and require a specific characteristic value.

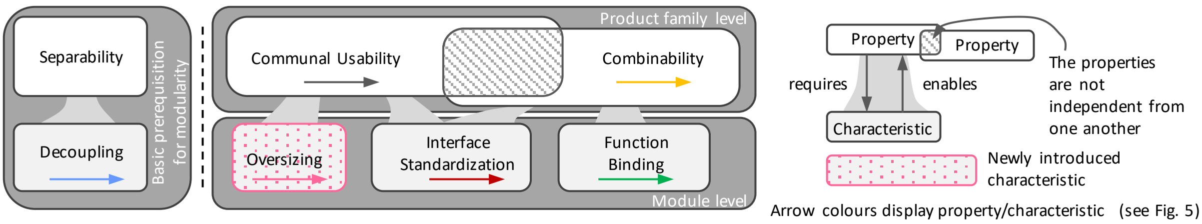

Figure 2: Nomenclature of product structure description

Connecting these relations of properties and characteristics to Salvador's definitions, the following set (Figure 2, left), based on Eilmus and Krause (2012), describes modular product family structures in the impact model and serves RQ2. The properties that describe the interaction of modules are given as 'communal usability' of modules in different product variants; 'combinability' is the ability to combine the maximum number of product variants by using the minimum number of components or modules; and 'separability' is the independence of modules from each other. Characteristics such as standardised interfaces therefore enable the combination of modules in different ways or can be used in different product variants (communal usability). Standard interfaces are therefore a characteristic that supports both properties. 'Function binding', meaning that functions of a product are fulfilled by just one and not several modules, enables better combinability of modules. 'Decoupling', describing a module whose binding to other modules is much lower than the binding of the components inside it, leads to separability. This set has a special role as being necessary for a modular product structure to even exist. Without separability there would be no modules.

In addition to Salvador's definitions, the new characteristic 'oversizing' is added to the existing set. Oversizing is often seen as a negative aspect of modularization (Hölttä-Otto, 2005; Perera *et al.*, 1999; Ulrich, 1994), however, it allows a module to serve the requirements of different product variants and is therefore the main enabler for modules to be used communally. Oversizing is the design of a module for the highest load case or functional requirement, making a module more or less oversized depending on the functions needed and the loads on a module in a product variant. The communal use of modules is mainly driven by modules fulfilling the requirements of several product variants (oversizing) and by the interfaces allowing the modules to be assembled in all desired product variants. To achieve combinability, decoupled modules that fulfil their functions without other modules is necessary.

3.2 Life phase effects based on literature

To be able to further contribute to RQ1, effects of modularity found in the literature study of Hackl and Krause (2016) have been expanded. Their paper provided a list of ten authors who describe the effects of modular product structures. The effects were then mapped to the life phases in which the effects occur. The literature analysis has been ongoing. 61 papers, mainly from management (31) and engineering (24) journals, have been found, including mainly journal papers and doctoral theses and one conference paper from six different databases (Science direct, Emerald Insight, ASME digital library, Web of knowledge, google scholar, research gate) published between 1990 and 2016. Different sets of keywords such as 'modularity', 'modular' and 'effect' or 'impact' were used for the search. 39 papers have been included in the current impact model (after discounting papers which did not contribute to the effects that modular product structures entail). Effects were grouped according to similarity of meaning, creating a list of 81 different effects that occur when modularizing products (Figure 3).

Figure 3: Modularization effects mentioned in literature in order of number of mentions

Figure 3 shows effects on the horizontal axis ordered by the number of occurrences of the effect. For example, the effect of 'parallel development' was named by nine authors i.a. (Baldwin and Clark, 2000; Ericsson and Erixon, 1999); each of the next four effects were named by eight authors, which are an increase of 'lot size' (Hansen *et al.*, 2002; Ulrich, 1995), a better 'upgradeability or adaptability' of the products (Chiu and Okudan, 2014; Arnheiter and Harren, 2006), the 'ease of derivation of new variants' from the existing ones (Meyer and Lehnerd, 1997; Lau Antonio *et al.*, 2007) and the decrease of 'number of parts' (Dogramaci, 2007; Hölttä-Otto, 2005). According to the context in which the effects were mentioned, they were allocated to the different product life phases in which they occur. The effect of 'parallel development' only appears in the product development phase, whereas the effect of a decrease in the number of parts ('No. of parts') affects two life phases (product development and procurement) as it is an inter-divisional effect. In general, most of the effects seem to appear in only one life phase. In the visualization of the effects and their interrelations (which were also provided by the authors), it appeared that even inside the life phases the effects are independent of one another. An intra life phase hierarchy is introduced in the model to improve its structure and readability. The layers are introduced as displayed in Figure 4 and described below.

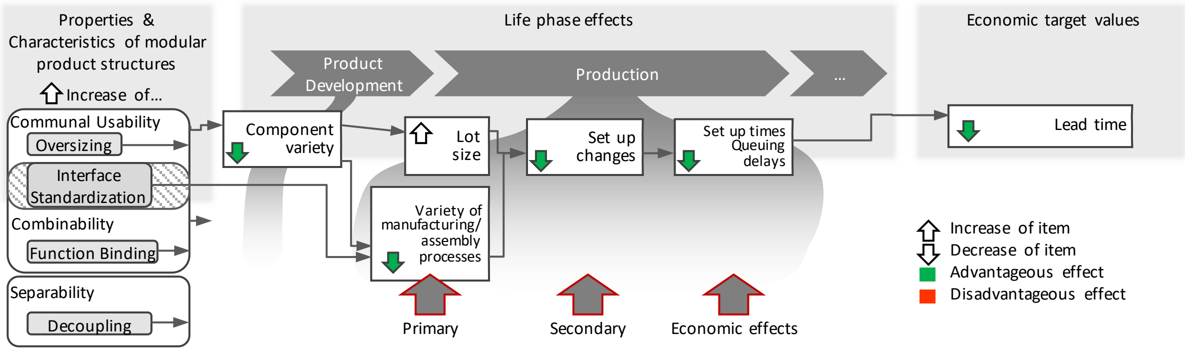

Figure 4: Differentiation of life phase effects

- Primary: These effects are directly influenced by the product structure
- Secondary: These effects are mainly influenced indirectly by the product structure and often mediated by primary effects
- Economic: Direct economic effects (subgroup of economic target values but still life phase specific)

Figure 4 shows that by increasing communal usability of modules, 'component variety' could be decreased. This would lead in production to the primary effect of a rising 'lot size', which is neither good nor bad for a company and hence the arrow is not coloured. In parallel, the variety of manufacturing or assembly processes could be reduced because of the decrease in component variety and higher interface standardization. Both effects (increased 'lot size' and decreased 'process variety') would lead to fewer set up changes, as a secondary effect, which again would lead to the economic effect of less set up time and fewer queuing delays, leading to a reduction in lead time.

3.3 Economic target values

The aim of modularizing product families is to offer a vast variety of products to the market by keeping internal variety to a minimum. This originates from minimal internal variety, leading to better economic target values. Having analysed the papers dealing with modularization, the described effects mainly contribute to a decrease of lead time (including flexibility, which leads to faster work) and to decreased cost. Other relevant target values like quality or risk are rather weakly described. Therefore, in the following model, the life phase effects are summarised to which target value they contribute to and whether the contribution is advantageous or disadvantageous (indicated by colour of arrows in Figure 4 & 5). A change which has been made to the previous impact model is that, according to Section 3.2, the life phase effects have one layer which is described as economical. These effects are part of the economic target values but life phase specific and therefore displayed in the life phases. E.g. the assembly time in production is part of the lead time which is an economic target value.

3.4 Impact model of modular product structures

This paper describes an impact model for displaying the structure and the idea of visualization. Not all effects are listed and the service phase is not displayed. A list of authors and effects in a complete impact model will be provided in a future publication. Combining the parts of the model by properties and characteristics, the relations between the product structure of a product family and life phase effects can be drawn (Figure 5).

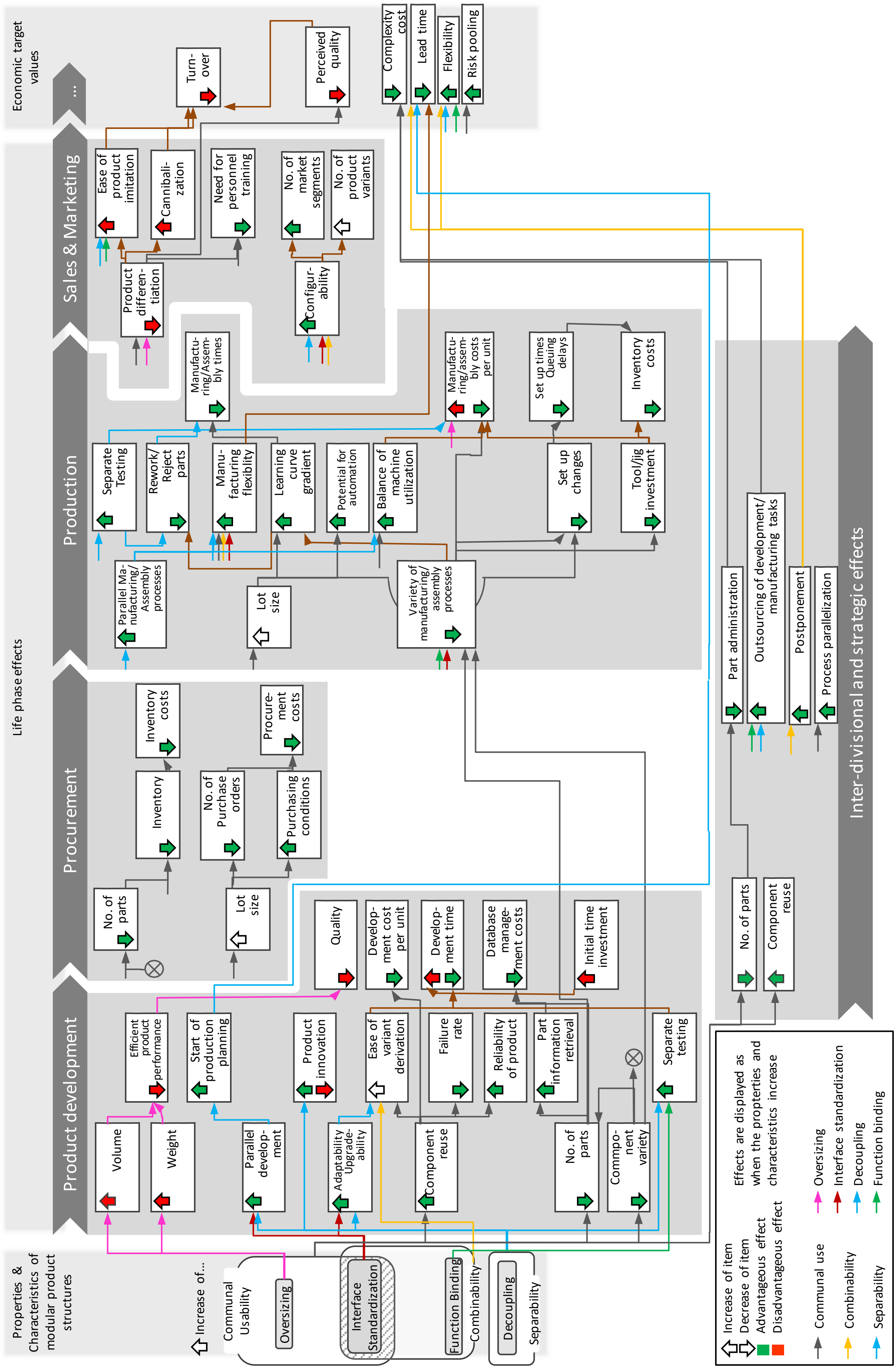

Figure 5: Modular product family structure impact model

The impact model shows the properties and characteristics of the product family structure, the effects which occur during product life phases, and which effects may occur when raising a property/characteristic in the product structure, contributing to RQ2. It shows whether an increase or decrease of an effect can be expected when adding a stronger parameter value of a property/characteristic. The effect is evaluated as being beneficial, detrimental or neutral for the company and is indicated by arrow colours in Figure 5. For example, an increase in the communal usability of modules in a product family will result in an increase in lot size of this module in procurement. This effect is neither positive nor negative and is therefore evaluated as neutral (no colour). A subsequent effect of bigger lot size may be better purchasing conditions, leading to a potential decrease in purchasing costs. These two effects are evaluated as beneficial for the company (green filling) because they lead to lower costs, which benefit the economic target value of cost. This does not necessarily happen. The dependence on certain boundary conditions for an effect to occur is addressed in Section 4.

Most of the effects are described in the life phases product development and production. The main reference values here are development time and associated development costs, and lead time in production. By defining a product structure, product development has an important scaling factor for production because the decisions made about product structure have an effect on production every time that a product variant is produced. Therefore, some relations are connected across life phases. The need of a product structure to be the best compromise for all life phases, also appears in the sales phase. Communal usability of modules (Figure 5, grey arrows) mainly helps to better plan and standardise processes in most life phases and is the most valuable driver for reduction of internal variety. However, it has negative effects in the sales phase when overused. Depending on the kind of product and the customer, communal use of components might lead to perceived lower quality by the customer, which will result in lower turnover. This might be the case more so in the consumer goods industry than in plant engineering. An increase in oversizing as a trigger for communal use of modules is present in every life phase (pink arrows). The efficiency of a product variant will not be as high as an optimized module anymore. Product performance, in terms of weight or unused functions, will decrease in a product variant. This oversizing could also lead to higher production costs per unit. For example, additional features like holes might be drilled in a module although not needed for the specific variant. However, reduction in number of parts (as a direct effect of communal use, which itself is driven by oversizing) would lead to reduction in parts administration. Reduced parts administrative effort occurs in every life phase when reducing the code numbers and leads to a decrease in complexity costs (Eilmus *et al.*, 2013). This effect of parts administration is located in the area of inter-divisional effects, meaning that it affects several life phases and is strategic. Other examples of strategic effects are the possibilities of 'postponement' or 'outsourcing of development or manufacturing tasks'. These effects have to be a company-specific decision on whether it would be expedient or not. As for readability of the model, it is possible to follow a particular arrow colour from a property or characteristic to get an overview of which effects might occur with an increase in specific properties or characteristics. It is also possible to start at a specific effect and work backwards to see which effect can be triggered by strengthening of a particular property or characteristic.

4 CASE SPECIFIC OCCURRENCE OF EFFECTS

The purpose of the impact model (Section 3.4) is to gain a better system understanding of the effects that modularity has in an industrial environment. This is the aim from both scientific and company perspectives. As mentioned in Section 3.4, effects do not always occur. For companies planning their product structuring, they need to know whether to expect an impact or not. Therefore, a case study of two companies was carried out, showing the relevance of boundary conditions of the effects. Table 1 shows the specifications of two companies that have modularized their products and who were interviewed about the effects that occurred as a result.

Table 1: Specifications of case study companies

	Company 1 (C1)		Company 2 (C2)	
Branch of industry	Elevator production		Powertools	
No. of employees	230		24,000	
Series Size	≈ 2 to 10 max.	Individual production	> 10,000	Series production
Sales numbers (per year)	≈ 200		> 100,000	
Supply Chain Strategy	Engineer-to-order (ETO)		Make-to-stock (MTS)	
Importance of Service Phase	High		Low - medium	
Product life-cycle time	≈ 30 years		2-10 years	

Company 1 (C1) is an SME carrying out ETO-based plant engineering; Company 2 (C2) is a much larger company that produces stock in far larger volumes.

The effects noticed in C1 were that they were able to decrease the 'failure rate' in development mainly through the 'reuse of given modules' from the newly introduced modular product structure. They were able to reduce their set up times and increase their learning curve, leading to fewer 'rework and rejected parts' in production. An effect which explicitly did not occur was a decrease in 'number of parts' in procurement, which can be explained by the high product lifespan and the importance of service in the company. Despite an increase in lot size, no reduction in procurement costs could be achieved.

C2 also increased the 'reuse of modules', leading to a decrease in 'failure rate' in development, and was able to decrease 'development time', which enabled a reduced time to market of new products, an important economic target value in this industry. In procurement, C2 was able to decrease the number of suppliers, which is a strategic decision, but the opportunity was created by the chosen product structure. Additionally, higher 'lot sizes' and therefore better 'purchase conditions', leading to a decrease in 'purchasing costs', could be obtained, which was described by the company purchaser as their most important driver for reduction in material costs.

Although both companies had increasing lot sizes, the subsequent decrease in purchasing costs (Figure 5) occurred in only one of the companies. Assuming both companies have well qualified purchasers the explanation for this could be that the decrease in purchasing costs appears in incremental steps, not continuously, when increasing the purchased lot size (Hohnen, 2014). This relation is displayed in Figure 6.

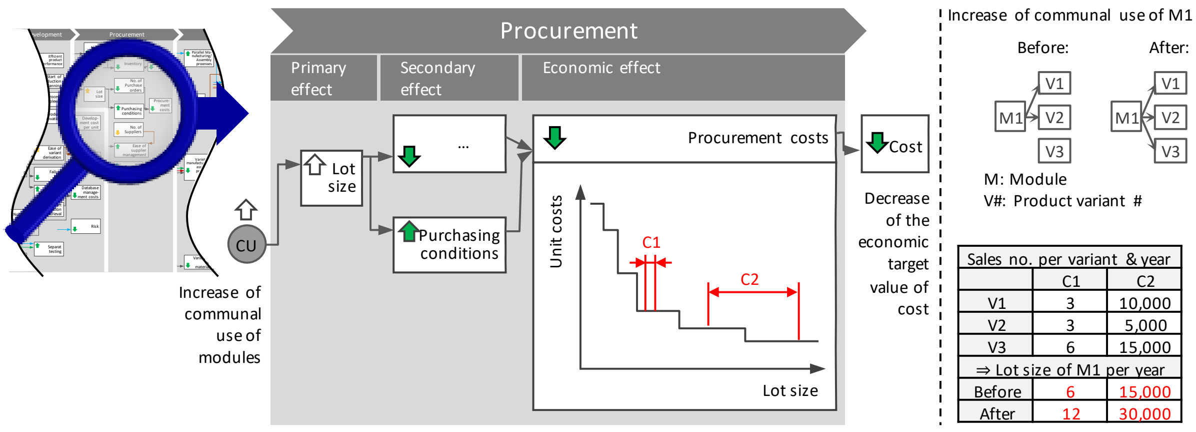

Figure 6: Boundary conditions for occurrence of reduced procurement costs in the case study companies C1 and C2

The higher sales numbers of C2, a series production company, result in a higher scaling effect of an increasing lot size than it does for a niche market producer like C1, which has generally lower sales numbers. For example, if C1 and C2 raised the commonality of module M1 (Figure 6, right), which can be used in an additional product variant V3, it would result in a doubling of lot size for both companies. It becomes more likely for C2 to pass the point for which volume discounts become possible because of the scaling effect of higher sales volumes (Figure 6, graph).

Another difference between the effects for both companies is the decrease in 'number of parts'. C1 said that the number of parts could not be reduced because of the long product life cycle of the products. Elevators have life cycles of around 30 years and the main income of the company is from service of the elevators. Therefore, all parts and documentation of older elevators must be kept. As the products of

C2 have lower lifespans, C2 does not have to deal with long service life cycles and can therefore reduce the number of parts, except in certain areas where downward compatibility must be assured.

5 DISCUSSION AND OUTLOOK

Having compared the occurring effects in a case study on two companies, the main weakness of the current model is that it does not show causalities: an effect that follows when the prior effect is present. The model presents mainly "… 'possible' effects rather than 'guaranteed' effects" (Hackl and Krause, 2016). A weakness of the properties and characteristics is that the entities are not independent of each other, as shown in Section 3.1. Providing metrics, like the number of standard and variant components (Eilmus and Krause, 2012) or a commonality index as a measure for different product structures (Martin and Ishii, 1996), may simplify the objective differentiation of product family structure concepts. The proving of metric sets on different product structures is ongoing.

The current model is a literature-based model that shows the relations between the product structural properties and characteristics of products and their possible effects on companies. It functions as an explanatory model to enhance understanding of the impact of modularity on production companies. The model provides an overall view of modularization and its effects on the life phases. Its strength lies in providing a bird's eye view instead of diving into just one or two effects and explaining these in detail for a specific case: Such a strategic model, connecting product structure and all main effects, is not currently present in the literature. Developing this impact model contributes to all three research questions by showing how increasing particular properties and characteristics achieves which effects and how that affects a company economically. Refining the existent set for definition of modular product structures to an interrelated set of properties and characteristics (Section 3.1) and relating these as causes to literature given effects contributes to research question 1 and 2. Connecting their economic outcomes serves research question 3.

To improve the information value of the model through case specificity, this literature-based model will be used as the basis for a survey of production companies that have implemented modularization to improve knowledge of which effects are most likely to occur in which company scenarios. The goal is to develop a model that can predict the boundary conditions under which certain effects will occur.

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