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EFFECTS OF MODULAR PRODUCT STRUCTURES ON LIFE PHASES AND ECONOMIC FACTORS

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1. Introduction

The development of modular product structures aims to provide a vast spectrum of variants to the market, based on minimal internal product and process variety. To achieve this in globalized markets with individual customer needs, specific effects are aspired to in each product life phase. For example, the reduction of procurement, production and storage costs can be achieved by effects of scale when improving the communal use of components in a product family. During recent decades, various methodical approaches have been developed that support the understanding of interrelations and how to modularize in practice. There are sources that describe effects of modularization for their method, for example, [Martin and Ishii 2002] predict a product structure that is more robust against changes when using their method. Properties and characteristics of modular product structures have been investigated and defined [Salvador 2007]. However, many of the methods exist "…in isolation from one other" [Simpson et al. 2012]. An overall model of the properties of modular product families and their effects does not exist [Harland and Uddin 2014]; however some researchers are currently working towards this to meet the need for consolidation [Andreasen 2009].

The overall aim of research on the impact of modularization on economic factors is to get a clearer understanding of the causalities. More precisely, a full model is aspired to that describes how modular product families affect the product life cycle and the overall performance of a company. Once a sound understanding of these causalities exists, the existing methods for modularization will be related to the model to be able to investigate which methods best help achieve an aspired effect. This may be of practical use in modularizing companies. In parallel with this paper, an industry case study investigating the effects of modular product structures in a specific firm is presented in [Windheim et al. 2016]. The first step here for achieving the aim above is to derive a first impact model based on literature. Therefore, in Section 2 general requirements for an impact model are set. Section 3 then gives an overview of existing impact models related to modular product structures. In Section 4, an initial literature-based impact model is derived that mirrors positive and negative effects. Section 5 concludes the model, and outlines limitations and the outlook for future research.

2. Requirements for an impact model

The development of an overall impact model generally involves two stakeholders: researchers and the practical users who introduce and apply modular product structures in industry. They have different and similar requirements of an impact model. For researchers, it is first of interest to show an overall picture of how the interrelations of individual causes on the product side act out and what effects follow as a consequence. Therefore, better understanding of the interrelations in companies must be aspired to. Later, actions in the form of methodical approaches on how to address the desired effects would be the

next aim. Therefore, the main goal for developing an impact model must be to bring structure to the complex relations of product modularity. The product-related view is then connected to the more product-strategic company view. The information gained from this model is also of interest for practical application. From several completed research projects in industry and the experience gained from talks to experts in various companies, a consistent picture has formed of companies often being afraid to introduce modular product structures if they have no experience of it. Companies can achieve much by introducing modular product structures. But compromises in some individual life phases have to be made in favour of a functioning overall system. Therefore, top management has to choose which areas of a company are most important [Robertson and Ulrich 1998]. Not all effects in all life phases can be achieved at the same time. Quantification of an impact model is important to know which scenario works best for the company. An example of such a decision is whether to introduce a new variant and acquire new customers at intra-company expense or to keep the internal variety low with a more communal solution, saving the extra development cost and time but possibly losing market share. Quantification would be beneficial as it would enable the forecasting of such decisions. For now, in this first step, the main focus of this publication is to create a model that describes the relations between product and economic level to be able to gain information and understanding. Therefore, practitioner usability is not currently of interest and a valid qualitative model is the first step.
For structuring the model, ordering the effects found will help readability of the model. Therefore, division into product life phases is carried out as it is an important differentiator in application of modularization because the effects of modular product structures vary between life phases. The requirements for an impact model are:

1. Division into life phases
2. Provision of cause (product-related) and effect (business-related)
3. End-to-end connection of cause, life phase effect and economic criteria of companies
4. Provision of qualitative tendencies toward change in the interrelations given in Requirement 3.

3. Existing impact models in literature

In literature there are few sources that provide an overarching view of the interrelations between modularity and economic factors, which shall be given here. To sum up the current state of research a research question is formulated:

- What impact models exist in current literature that describe the relations between modularity and its effects on economic factors?

In the literature study seven sources were found that provide an actual impact model of modularization. The first one comes from [Harland and Uddin 2014]. Their literature-based investigation concentrates on the effects that product platforms have and how these effects are interrelated. They especially focus on how product platforms foster lean development and production. The relations between the effects were drawn based on basic economic relations. [Harland and Uddin 2014] structure their model into direct and indirect effects that either affect the competitive advantage of a firm or its cost. Both goals support the aim of increasing the profit of a firm. Generally, the structure of the model is a hierarchical influence model. Life phases are not considered. As cause of the effects, product platforms as a whole entity are given. On the technical-functional side, commonality is the only detailed reason given. They state that only positive effects are considered in the model but that negative effects might occur in practice, which they did not address.
Several publications can be found that derive impact models based on empirical studies using statistics. [Lau et al. 2007] state, based on literature, that product modularity has a positive effect on price (low), product quality, delivery time, flexibility and customer service, all of which they declare as measures of competitive capability. They state that these five competitive capabilities have a positive influence on product performance. Their statistical analysis shows that product performance is increased by product modularity, which supports the literature. As causes they name higher flexibility and delivery. Better customer service, which is also positively affected by product modularity, indirectly increases product performance. In their study, no significant relation could be found between product modularity and

lower price, and product modularity and product quality. This model is fully located on the product strategic side of the impact model aspired to in this work, as flexibility, given as a reason therein, is caused by product related effects, which are not given.

[Danese and Filippini 2013] also use statistics to analyse the impact that modularity has on the time required for new product development and product performance. They verify their hypotheses that product modularity can lead to a decrease in time required for new product development and can positively affect product performance. Supplier integration can also be positively affected. The effects and causalities in this work generally enable product modularity to improve time and performance at a high level. [Gualandris and Kalchschmidt 2013] found that process modularity can reduce the effect of supplier failure, whereas product modularity cannot. Considering that product modularity is "…an enabler of process modularity…" [Gualandris and Kalchschmidt 2013], an indirect effect of risk distribution was found. They state that both product and process modularity act indirectly on flexibility and supplier failure. [Sohail and Al-Shuridah 2015] found that product modularity acts positively on cost, product quality, production, flexibility, and lead time. [Worren et al. 2002] found another link, stating that modularization has a positive effect on the variety of product models.

Several databases were used for the literature search. The search criteria were not limited to a certain slot of years. Most of the papers found on impact models of modularization were published during the last 10 years, indicating that there is need for and interest in more detailed descriptions of the overall interrelations. More literature on the current state of research is available that is not mentioned here due to the limited number of pages. In most of these analyses the studies commonly describe relations that modularity has on certain factors. Relations to the product structural side, with descriptions of their properties, are not given. The explicit division into life phases and allocation of effects to them were not undertaken.

Most of the effects described have a positive effect on a firm's performance. As most of the papers come from management journals and therefore have a management perspective, referring to modularity as a catalyst for the mentioned and desired effects is sufficient for their purpose. For a deeper understanding of the causes on the technical functional side, more specific relations are necessary to modularize in a way that supports the desired effect. For example, if a decrease in mounting costs and time is required, attention should be on interface standardization. Interface standardization leads to effects of scale in production because of better utilization of mounting tools and the use of the same mounting processes, which is followed by a possible decrease in time and cost in production [Salvador 2007], [Harland and Uddin 2014]. In summary, stating that modularity is the general cause of the effects outlined here is not sufficient if the product structure is supposed to be changed specifically to achieve targeted life phase or strategic effects. Therefore, information on how a modular structure leads to the aspired effects is needed.

[Salvador 2007] published a broad literature review on product development-related modularity, including understanding and definitions in the community. He derived five terms that characterise modularity. The terms, referred to as 'properties of modular product structures' in this paper, are:

- Commonality, Combinability, Interface standardization, Function binding and Decoupling.

[Salvador 2007] sums up these five terms from the theoretical domain to three terms in the empirical domain: commonality, separability (including decoupling), and combinability, which includes functional binding and interface standardization. For technical functional-related structuring, the properties are taken to describe the causes of modularization effects.

[Boer 2014] developed a model, which takes some product modularity characteristics as causes of investigated effects. These are standardised interfaces, standard modules for communal use and specific functions that are fulfilled by enclosed components. The structure of this model differentiates characteristics that lead to product effects, organizational effects and performance effects, which were derived from a literature study. [Fixson 2006] provides an entire cause-effect chain, considering function-component allocation and interface characteristics as drivers for life phase effects, summing them up as impacts on cost and time. Table 1 shows a comparison of the literature sources for the requirements of an impact model.

Table 1. Comparison of existing impact models for requirements from Section 2

Literature source \ Requirement	Life phase view	Cause (product structure related)	Life phase related effects	Strategic overall effects	Relates cause and effect qualitatively
Harland and Uddin 2014	○	○	◑	●	◑
Lau et al. 2007	○	○	○	●	●
Danese and Filippini 2013	○	○	○	◑	●
Gualandris and Kalchschmidt 2013	○	○	○	●	●
Sohail and Al-Shurida 2015	○	○	○	●	●
Worren et al. 2002	○	○	○	◑	●
Boer 2014	◑	◑	◑	○	◑
Fixson 2006	●	◑	◑	◑	◑

● Mainly considered ◑ Partly considered ○ Not/weakly considered

The difference between the papers from management and engineering, such as [Fixson 2006] and [Boer 2014] is that the latter provide product structural causes that show effects on product life cycle. The management-related papers, such as [Harland and Uddin 2014], take the life cycle effects and connect them to overall economic aims, all leading to increased profit. The sources using statistics leave detailed life cycle effects out and give general but statistically proven impacts, which modularity generally has on company aims. The connection of worlds (product structural and business-related views) has so far only partially been given (by [Fixson 2006]) and is therefore extended in the following section. A combined model, dividing modularity into its properties that lead to life phase effects, and relating them to the overall economic criteria, will be introduced.

4. Derivation of a literature-based impact model of modular product structures

The following model describes cause and effect chains in the way that they are present in the business environment of production companies. Products run through the whole life cycle and their product structures influence how processes in the life cycle proceed. The model shows how a change in the properties of the modular product structure acts on economic factors. Therefore, the investigated life phase effects are collected from the product life cycle, related to the properties, and summed up to strategic effects and economic factors. Insights into the system relations of modular product systems are expected from this.

Product life phases in a manufacturing firm, as given in [Ehrlenspiel and Meerkamm 2013], are adapted, concentrating on product definition and development, production and assembly, sales, use and service, leaving out the recycling phase as no literature on it was found. In addition, procurement, commonly seen as part of the production phase, is seen here as being a main driver of manufacturing cost and is therefore considered separately [Ehrlenspiel and Meerkamm 2013]. The properties of modular product structures are taken to describe the technical-functional view and, therefore, the product-related view on modularization. They are then connected to the effects that they may cause in the life phases of the product. The effects in the life phases themselves have an impact on strategic target values and economic criteria. These show the product strategic side of modularization related to management. Figure 1 gives the structure of the model.

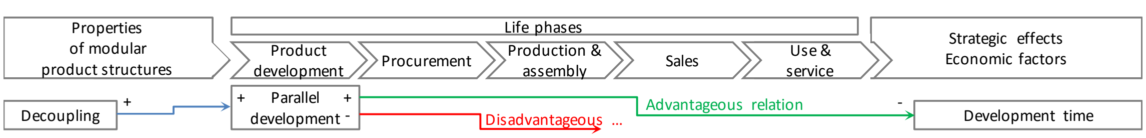

Figure 1. Structure of the impact model

The relations of the model are unidirectional from left to right. The nomenclature is taken from the initial reference model of [Blessing and Chakrabarti 2009], indicating increase "+" or decrease "-" of the object. In the example, a possible increase in parallelisation of development tasks in the development life phase is described because of an increased inter-modular decoupling [Baldwin and Clark 2000]. This leads to a decrease in development time. The colours of the lines in the impact models ensure better readability on the left, and indicate advantageous (green) or disadvantageous (red) relations on the right side. The life phase effects found in literature are given in Table 2.

Table 2. Possible life phase effects caused by modular product structures

Product Development			
Life phase effect	Literature	Life phase effect	Literature
High time investment for product family development	[2,3,8]	Decreased complexity	[6]
Easier adapdability	[2,3,4]	Parallel develompent	[4,6,7,10]
Easier variant derivation	[1,3,6,7]	Lower no. of interfaces	[5]
Increased efficiency in development	[8,10]	Oversizing (potentially larger, heavier and less energy efficient)	[6]
Increased innovation in development	[6]	Increased upgradeability	[2,6]
Decreased innovation in development	[2]	Increased component reuse	[3,5,6,8]
Lower failure rate	[3]		
Procurement			
Fewer part numbers/variety of modules	[2,3,5,6,8]	Increased specs for supplier	[6]
Effects of scale (lot sizes), better purchase conditions	[2,3,5]	Less inventory	[2]
Increased flexibility/predictability	[2]	Simpler supplier management (less part numbers)	[2]
Increased carrying cost (increase of lot sizes)	[5]	Standardization of purchase (due to postponement)	[2]
Production & assembly			
Less variety of assembly processes	[8,9]	Less non-value adding processes - transport, setup time	[2,3]
Less complexity in production	[3,10]	Decreased work in progress	[2,8,10]
Potential automation of production, assembly and test	[9]	Steeper learning curve (higher productivity, less mistakes in production)	[2,3]
Increased productivity (learning curve)	[2]	Fewer/simpler tests (effects of scale)	[2]
Simpler interfaces	[5]	Bigger lot sizes (effects of scale)	[4,5,8,9,10]
Increased flexibility in production	[1,7,8]	Less rework (effects of scale)	[2]
Less need for tool and jig investment	[2,3,8]	Less effort for assembly	[1]
Oversizing	[6]		
Sales & marketing			
Less effort for advertisement	[3]	Reduction in global differences	[3]
Less need for staff training	[3]	Easier product integration	[1]
Increased no. of market/price segments	[3]	Fewer number of parts	[8]
Decreased product differentiation	[8]		
Use & service			
Less deassembling effort, process complexity	[1,9,10]		
Simpler system upgrade and reconfigurability	[9]		
Increased ease of service	[2,7,9,10]		
Decreased variety and no. of spare parts	[2,3,8,10]		
Faster service (reactivity)	[2]		
Less management effort (less complexity)	[2]		
Oversizing	[6]		
Less training of service personnel and customers	[3,10]		

[1] Boer 2014
[2] Chiu and Okudan 2014
[3] Harland and Uddin 2014
[4] Hansen et al. 2002
[5] Hohnen 2014
[6] Hölttä-Otto 2005
[7] Lau et al. 2007
[8] Robertson and Ulrich 1998
[9] Salvador 2007
[10] Fixson 2006

In the next sections, the impact models in the life phases are given and related to their cause and economic impact. In Figures 2-6 the cause of effects that are not connected to any property is modularity and has not been further specified. Therefore, these effects are present but their cause is not further specified. All of the effects described are mainly 'possible' effects rather than 'guaranteed' effects. Most of them will not appear, and the increase in one effect may reduce another effect in the same or another life phase. The literature that underpins the figures in the next sections can be found in Table 2.

4.1 Product development

The main findings from the literature survey of product development are shown in Figure 2. [Harland and Uddin 2014] and [Lau et al. 2007] describe an easier derivation of new product variants due to modularity. [Boer 2014] says combinability is the cause, whereas [Hölttä-Otto 2005] gives decoupling of modules as the reason (Table 1). Simpler variant derivation may then lead to increased flexibility in development and decreased development costs [Harland and Uddin 2014].

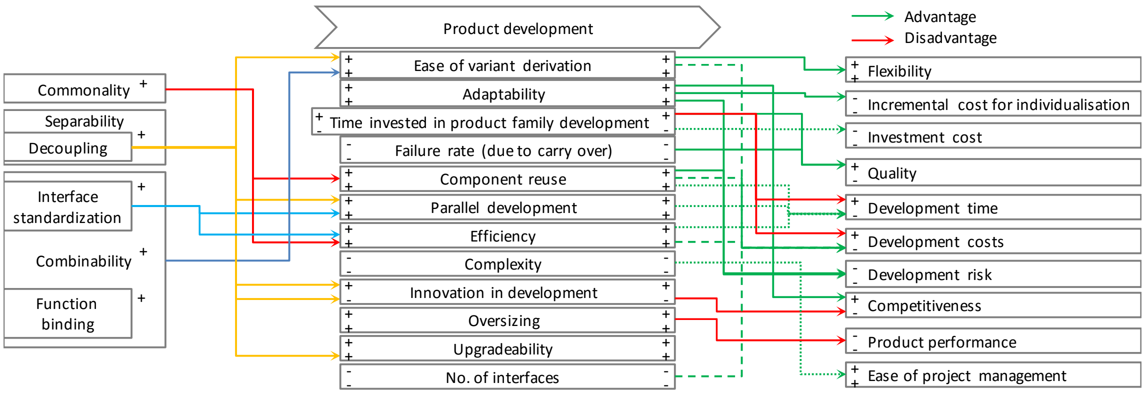

Figure 2. Impact model of the product development life phase

[Hansen et al. 2002], [Harland and Uddin 2014], and [Chiu and Okudan 2014] relate modularity to increased adaptability in the products developed. No relation to properties is given. This effect leads to higher competitiveness and lower development risk, as well as reduced incremental costs for individualisation of products. The time necessarily invested in product family development is firstly negative, leading to increased development costs [Chiu and Okudan 2014] though creating potential for an increase in quality. As counted per single product, [Robertson and Ulrich 1998] state that the time invested is negative and reduces investment cost and therefore the risk. The failure rate in development can be decreased by carrying over components, leading to better quality. Component reuse, as a central effect of commonality, leads to a decrease in development time, costs and risk. The parallel development of components caused by decoupling and interface standardization reduces development time. Commonality may cause increased efficiency in development. At the same time, complexity decreases due to better structured product architecture, which leads to simplification of project management. Contradicting relations in development innovation can be found. A rise and a fall due to decoupling is described, which leads to reduced competitiveness and may be caused by loss of understanding of the whole product system because of decoupled modules and development. This is accompanied by an increase in oversizing, possibly leading to a decrease in product performance. Increased upgradeability due to decoupling and a reduced number of interfaces, which decrease development costs, are additionally described.

4.2 Procurement

In the procurement life phase, not many connections to causes or strategic effects were given (Figure 3). Commonality can reduce the variety of parts and therefore part numbers. Reduced procurement and storage costs follow. Modularity increases the number of ordered standard parts, meaning lot size, decreases number of parts in inventory and increases reactivity and predictability. Higher lot sizes may counteract the decreased number of parts, increasing inventory and storage costs. At the same time, procurement costs can be reduced because of volume discounts. Postponement strategies enable standardisation of purchasing and supplier management becomes easier. Specifications for suppliers may increase because modules have to be delivered which fit the product family. Therefore, costs for modules may rise.

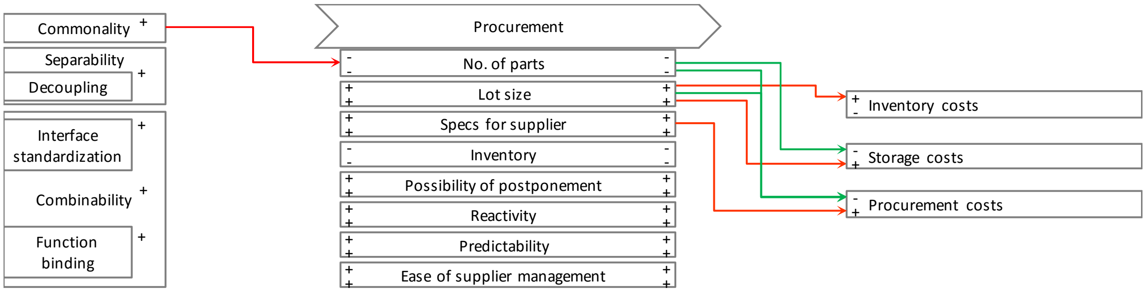

Figure 3. Impact model of the procurement life phase

4.3 Production and assembly

The main drivers of modularity in production are commonality and interface standardization (Figure 4). Communal modules lead to an increased lot size, which is followed by reduction in manufacturing costs, including setup and testing costs. Commonality leads to learning curve effects, reduced work during progress and assembly effort. Decreased lead time and manufacturing costs can also follow.

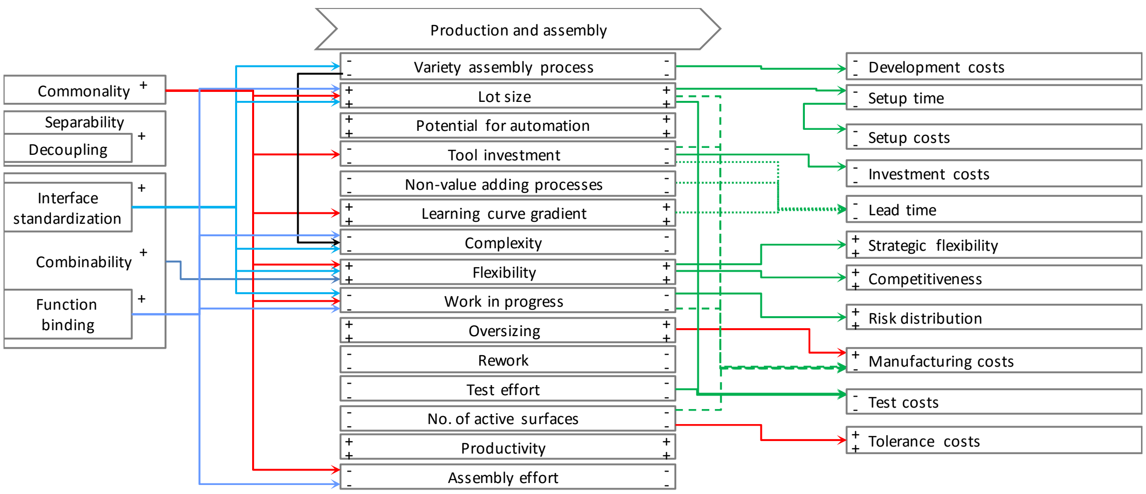

Figure 4. Impact model of the production and assembly life phase

Standard interfaces lead to less variety in the assembly process, which is followed by decreased costs in development of production and assembly processes. Non-value adding process time can be reduced which may lead to a lower lead time in production. Flexibility can be increased because modules can be flexibly combined [Lau et al. 2007], communally used [Robertson and Ulrich 1998] and the interfaces allow for a more flexible use of production lines [Boer 2014]. The negative consequence of oversizing is increased manufacturing costs. The main benefits that can be achieved in production are decreased lead time and cost.

4.4 Sales and marketing

In the sales and marketing life phase, several effects of modularity were found but only a few connections to its properties. [Harland and Uddin 2014] state that advertisement and personnel training efforts can be decreased, which leads to reduced costs for advertisement and sales generally. Being able to increase the number of markets or price segments and therefore being able to decrease global differences with only one product family increases competitiveness and simplifies global operations. Less part numbers benefits sales costs due to the time that can be saved in offer preparation. [Boer 2014] describes a simplification of the integration of products through combinability, which may lead to greater competitiveness because newly developed modules can be more easily and quickly integrated. Oversizing arising from commonality and the fact that some functions are fulfilled by the same components leads to less product differentiation, which can decrease sales volumes. Sales figures and competitiveness are therefore closely related. Figure 5 shows the effects described.

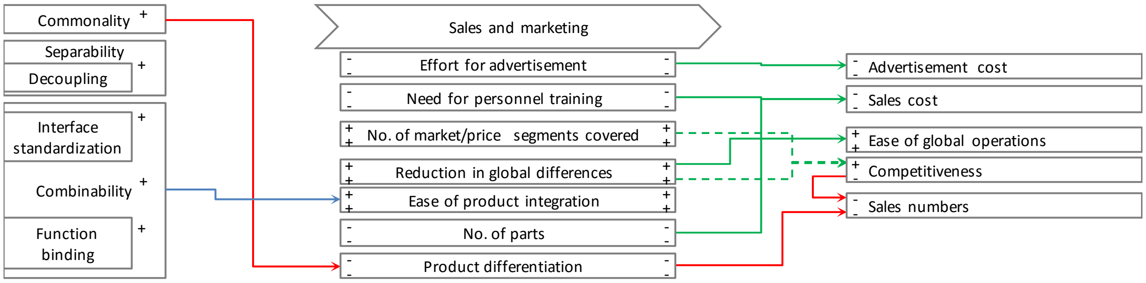

Figure 5. Impact model of the sales and marketing life phase

4.5 Use and service

In the life phase of use and service the properties commonality and decoupling are the main relevant drivers. Decoupled modules with reversible standardized interfaces decrease the disassembling effort required [Salvador 2007] and [Boer 2014], which leads to easier service, reconfigurability for the producer and better upgradeability for the user. These effects are also driven by decoupled modules. Figure 6 shows the effects found in the use life phase.

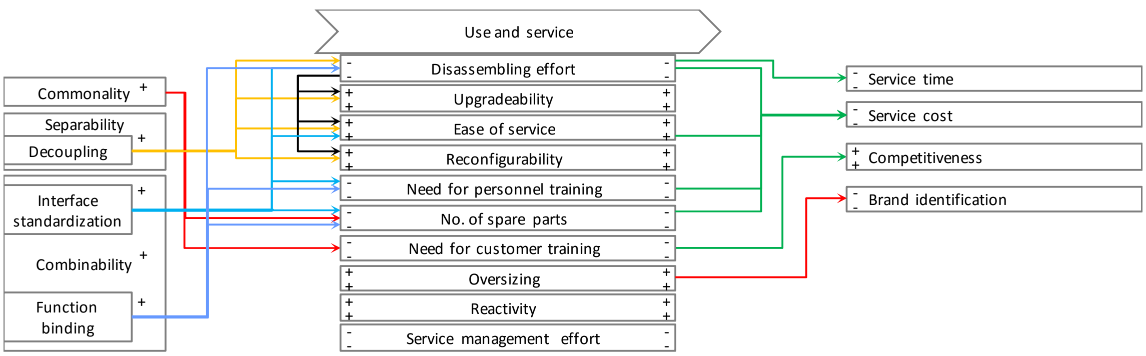

Figure 6. Impact model of the use and service life phase

A reduction in training for personnel and customers may be achieved. Service costs may be reduced and competitiveness can be increased because the customer benefits from saving money on training in the products in a product family. The communal use of modules lowers the number of spare parts in stock, reducing storage and therefore service costs [Robertson and Ulrich 1998], [Chiu and Okudan 2014]. The oversizing needed to fulfil several size ranges reduces brand identification and can therefore decrease the competitiveness of a company [Hölttä-Otto 2005]. Reduced management effort in service was described by [Chiu and Okudan 2014].

5. Conclusion, limitations and outlook

The goal of this paper is to provide a system view of potential influences of modular product structures in an industrial environment. Requirements of an impact model were set out in Section 2. The models developed in Section 4 display the possible consequences in the life phases or departments of a firm that result from modularization. To contribute to understanding of overall system behaviour, a literature study was conducted; the technical-functional view (properties of modular product structures) and the product strategic view (economic factors) were connected by life phase effects. Positive and negative effects have been found across all life phases but positive ones (green relations in Figures 2-6) predominate. This indicates that modular product structures may be advantageous in companies struggling with variety. The reviewed articles showed that some effects can be found in several life phases of the product life cycle. For example, procurement and production are affected by increasing lot size. Increasing costs for inventory and storage and falling costs due to volume discounts in procurement and manufacturing costs in production can result from increasing lot sizes. Other effects in production, such as reduced work in progress, appear in just one life phase.

Across all life phases, commonality is the effect driver most named. The communal use of components is one of the main advantages that decrease the internal variety of modular product families but simultaneously allows high external variety of products on the market. In the development phase, literature mainly mentions commonality and decoupling as effect drivers. Procurement also profits from commonality. Effects caused directly by the other properties were not found. In production and assembly (besides commonality leading to increased lot sizes), standardized interfaces enable simplification of assembly processes. Both save time and costs in this phase. In the sales phase, the only relations found to the properties are the loss of product differentiation because of commonality and a simpler variant integration due to combinable modules. But a configure-to-order strategy becomes possible, reducing planning and lead time. In use and service, profits mainly come from decoupling of components, interface standardization and function binding, which simplifies service. The impact models developed show a system of connections. As described in Table 1, the existing models in literature mostly focus on business effects. Only [Fixson 2006] gives end-to-end cause and effect chains, concentrating on function binding and interfaces. [Hölttä-Otto 2005] also focuses on one property, naming decoupling as the main driver for increased innovation potential, easier variant derivation and parallel development. The models presented display a collection of investigation results from several experts in the field of modularization, which benefits overall system understanding. Read from the right to the left, if, for example, a reduction in development time needs to be achieved, the reuse of components, achievable with an increase in commonality, is an enabler. But the model (Figure 2) shows that a time investment to develop the modular product structure is necessary in the first place; this makes the aforementioned benefit a long-term advantage. An increase in commonality is often achieved by oversizing, which may affect several life phases, such as reduced product performance, potential loss of brand identification, and higher manufacturing costs in production (Figures 2, 6, and 4). Not every effect necessarily occurs. For example, loss of brand identification may occur in the automobile industry rather than the machine tool industry. Observations from a two-year industry project have shown that after investing two years in the development of modules, the development time in processing of orders, for one specific module could be reduced by more than half. But a reduction in part numbers could not be observed because the company needed to provide spare parts for a long time due to service contracts. Boundary conditions, such as industry branch, company size and sales volumes, play a central role, whether or not effects occur, and have to be integrated into the model.

The model is limited by its lack of completion. There might be more effects that have not yet been taken into account. The size of the model is also a drawback. A model of the whole system would create better system understanding but breaking it down into individual life phase figures was necessary to make it readable on paper. Some lines seem to be missing in the model; for example, the decreased need for customer training (Figure 6) occurs not just because of the use of communal components but because the functions are fulfilled by the same modules and the user will be more easily able to adapt to a new variant. In procurement, the use of standard interfaces would simplify finding purchased parts. The missing lines should be investigated and proved in future research. To enable better qualification and quantification of the causalities, metrics will be applied to measure the degree of commonality, separability and combinability to support or disprove the causalities.

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