

Brylowski, Martin; Ludwig, Maximilian; Kersten, Wolfgang; Schultze, Wolfgang

## Conference Paper

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Martin Brylowski, Maximilian Ludwig, Wolfgang Kersten, and  
Wolfgang Schultze

# Product Modularization in Integrated Supply Chains: A Product Life-Cycle Phase Specific Concept for Effect Allocation



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# Product Modularization in Integrated Supply Chains: A Product Life-Cycle Phase Specific Concept for Effect Allocation

*Martin Brylowski<sup>1</sup>, Maximilian Ludwig<sup>2</sup>, Wolfgang Kersten<sup>1</sup>, and Wolfgang Schultze<sup>2</sup>*

*1 – Hamburg University of Technology - Institute of Business Logistics and General Management*

*2 – CEPRA – Center of Performance Research and Analytics*

**Purpose:** Product modularization and supply chain integration have established themselves as efficient methods for complexity management, but a holistic view of their effects has rarely been studied. For this reason, we demonstrate a concept which presents these effects along the product life-cycle phases (PLCP) and the strategic success factor (SSF):

**Methodology:** We applied a systematic literature review and carried out 13 semi-structured expert interviews to cover the perspective of science as well as practice. Using qualitative content analysis, the effects of product modularization in integrated supply chains is elaborated. The effects were allocated to the appropriate PLCP and subsequently assigned to the affected SSF.

**Findings:** We found positive and negative modularization effects in each phase of the product life-cycle: development, procurement, production, sales, and after-sales. Within the appropriate PLCP, the effects were allocated to the SSF: cost, time, quality, flexibility, and risk. Scientists as well as practitioners are aware of the positive effects of modularization. Negative effects are largely neglected in both perspectives.

**Originality:** The developed concept provides a holistic view of product modularization effects under consideration of an integrated supply chain. Besides the PLCP specific effects are assigned to the affected SSF. This enables a structured and categorized assessment of modularization effects in integrated supply chains and reveals hidden as well as undesirable side effects for science and practice.

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## 1 Introduction

In today's competitive environment companies are facing numerous requirements: Customers are becoming more and more demanding regarding the performance and individuality of products, which increases the number and variety of new product launches. At the same time, the more intensive interaction between mechanical and electronic product components leads to an overlapping of different technology and innovation cycles. Lau, Yam and Tang, (2011), consider the electronics industry to be the industry with the shortest product life-cycles, in which product development is often influenced by the degree of modularity of the product. Concerning drive technology, the number of electronic components of products has risen continuously. From a cost perspective, this change requires a separate optimization of the technology and innovation cycles compared with those of traditional hardware (Müller, 2001, p. 52). Modularization enables those functions, that are subject to the same technology or innovation cycle, to be combined in one module (Müller, 2001, p. 52). This simplifies the replacement of modules with different life-cycles since it is no longer necessary to replace the entire product if only individual components need to be adapted (Müller, 2001, p. 52).

Furthermore, modularization is influenced by the increasing cooperation between companies and supply chain management has been established in many places (Schilling, 2000, p. 327). The design of the product architecture has become indispensable for the design of the interfaces between supplier, producer, and customer and has a considerable influence on product life-cycle costs (Schilling, 2000, p. 327). For example, from the pro-

curement side, modular sourcing can be established to reduce development costs and use the development competencies of suppliers (Schilling, 2000, p. 327). In the after-sales area, spare parts management can be mapped more effectively, and, from the customer's point of view, switching costs between different suppliers are reduced (Schilling, 2000, p. 327).

These effects represent only a part of the potential of product modularization with regard to product life-cycle costs (Ulrich, 1994, p. 224). Through the physical decoupling of modules and the decoupling of development and production processes, many other effects can be related to internal company procedures and cooperation in supply chains (Ulrich, 1994, p. 224). Along the product life-cycle, in addition to the direct monetary effects, changes in the strategic success factors (SSF) of time, quality, flexibility, and risk also arise, which can be attributed to costs (Kersten, Lammers and Skride, 2011, p. 24). The diversity of potential product modularization effects reflects the complexity that companies face with product modularization projects. While a comprehensive, structured and transparent presentation of the direct and indirect product modularization effects on product life-cycle costs, considering supply chain activities, could serve as a basis for orientation and decision-making, the literature provides only fragmentary approaches for solving this problem.

Product modularization and supply chain integration have established themselves as efficient methods for complexity management, but a holistic view of their effects has rarely been studied. For this reason, we demonstrate a concept which presents these effects along with the product life-cycle phases (PLCP) and discusses the following research question in this paper:

- 1) Which product life-cycle phase (PLCP) specific product modularization effects result from supply chain integration in the drive technology industry?
- 2) How do those effects affect the strategic success factors (SSF) of a company in the drive technology industry?

The remainder of the paper is structured as follows. Section 2 describes the methodological approach. Section 3 describes the Product Life-Cycle Phase Specific Concept for Effect Allocation and assigns the main effects of product modularization in integrated supply chains to the appropriate PLCP and SSF. Section 4 shows the results and section 5 completes the article with a conclusion including the managerial implications and advices for further research.

## 2 Methodological approach

The allocation of product modularization effects in the integrated supply chain to the appropriate PLCP and SSF of a company follows a five-step research design which can be seen in figure 1.

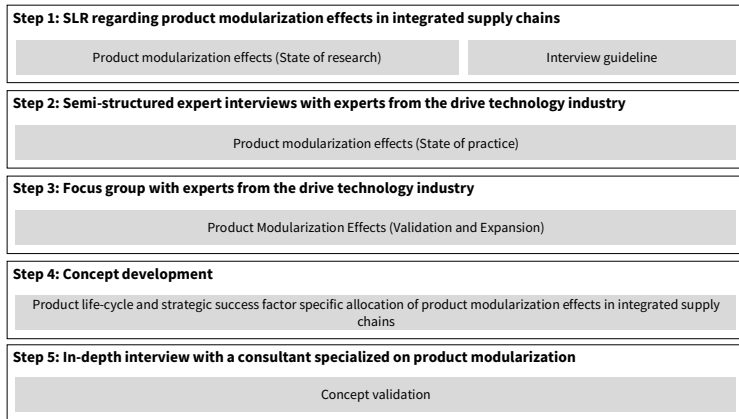


Figure 1: Steps of the methodological approach

First, a systematic literature review (SLR) is applied to extract product modularization effects from scientific publications. This step is also used to develop a guideline for semi-structured expert interviews. One of the aims of this paper is to present the state of the art on the topic of product modularization related to the drive technology industry. Accordingly, the experts participating in the interviews and the focus group are persons exclusively working in this field. Consequently, following the SLR, 13 semi-structured expert interviews are conducted to assess the effects of product modulari-

zation in the drive technology industry. The results of both research methods are then discussed in a focus group and extended by further effects. The focus group consists of six experts, all of them previously participated in the expert interviews. The next step is the concept development and thus the allocation of the effects to the appropriate PLCP and SSF of a company. Finally, an in-depth interview is applied to validate research findings. The in-depth interview was conducted with a consultant who is specialized in product modularization. The interviewee has a broad knowledge regarding the effects of product modularization and is therefore ideally suited for the validation of the allocation. The most important person- and company-related information can be found in the appendix. The data generation and validation processes are described in detail in the following chapters.

### **Step 1: Systematic literature review**

In management research, the SLR is an important instrument to manage the diversity of knowledge (Tranfield, Denyer and Smart, 2003, p. 208). Mulrow (1994, p. 597) discusses a variety of arguments why a SLR can be seen as a very efficient method for identifying and evaluating extensive literature. The main difference to traditional research is the introduction of a replicable, scientific, and transparent process that aims to minimize distortions and random errors in systematic literature research (Cook, Mulrow and Haynes, 1997, p. 377). To define uniform steps and to ensure scientific quality, the SLR carried out in this study is based on the procedure described by Tranfield, Denyer and Smart (2003).

At the beginning of the SLR, a review committee should be set up to avoid controversies about the inclusion and exclusion of articles (Tranfield, Denyer and Smart, 2003, p. 214). In the SLR carried out for this work, the



review committee consists of the authors that deal with the topic of product modularization for research purposes. After the review committee is set up, the objective of the SLR must be defined (Tranfield, Denyer and Smart, 2003, p. 214). This is already apparent from the motivation and research questions of the present paper.

The identification of relevant research begins with the selection of databases where scientific publications can be found (Tranfield, Denyer and Smart, 2003, p. 215). In this paper "Scopus" and "Web of Science" are selected, which are considered as the largest databases for peer-reviewed literature in various research areas. The data extraction from the databases took place on the 1st of January 2020. Subsequently, keywords and a search string are identified, which are built up from previous preliminary research, literature, and discussions within the review team (Tranfield, Denyer and Smart, 2003, p. 215). The selected search string is divided into three categories with the focus on the keyword "modular\*". The search string is used in such a way that each publication found contained modularization in the title, abstract, or keywords. Besides, the keywords "effect", "impact", "implication", and "change" are included, which indicate effects in connection with modularization. This ensured that publications could be found that contained the effects of modularization. Besides, the keywords "supply chain", "supplier", and "value chain" are used to obtain hits linking modularization with the supply chain or value chain perspective. To limit the number of search results and thus exclude irrelevant literature, the

search term is reasonably combined using Boolean operators ("AND" and "OR") are illustrated in Figure 2.

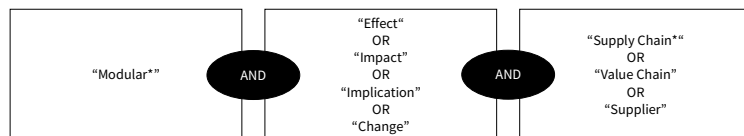


Figure 2: Search string used for the SLR

With those search strings a total of 828 search results were generated on Scopus and Web of Science. After the removal of duplicates, 644 publications remained to be examined. In a next step publications which are not relevant for answering the research question were filtered out (Tranfield, Denyer and Smart, 2003, p. 215). For this purpose, two filter criteria were established. First, all publications that are not written in German or English were filtered out. Second, during title and abstract screening only publications dealing with product modularization in the context of supply chain management were kept. After these steps, 128 relevant publications remained. The subsequent full-text screening was carried out using the same filter criteria, with the addition that product modularization must be treated as a central object of investigation within the studies. A total of 71 publications were identified that meet all filter criteria and thus prove to be suitable for the data extraction. 16 additional publications were added that proved to be relevant in the backward citation. For the final data extraction, 87 articles remained and are shown in detail in the appendix. Figure 3 shows the number of relevant publications after each filter step.

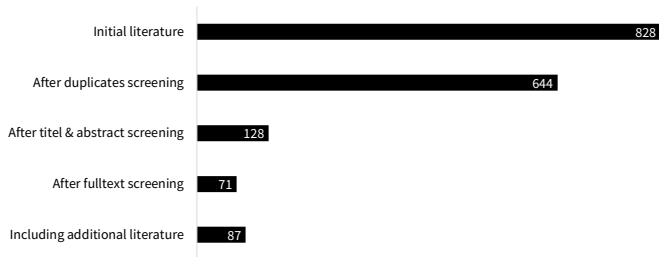


Figure 3: Number of relevant publications

The subsequent extraction and summarization of the data were carried out by using the Citavi 6 software to code and qualitatively analyze all corresponding modularization effects. The literatur analysis was based on Mayring (1994) using the coding method. This contains a summary of identical aspects from the identified publications and their reproduction by a new statement (Mayring, 1994, p. 164). By coding the individual modularization effects, a code structure is created, which is hierarchically structured according to the relationships between the individual modularization effects.

## Step 2: Semi-structured interviews

In order to identify product modularization effects in the drive technology industry as comprehensively as possible, 13 expert interviews were conducted within this paper. Those are classified in the category of semi-structured interviews and lasted between 45 and 90 minutes. Besides, these are guideline-based interviews, which differ from open and narrative interviews. An interview guideline contains questions that are asked to the interviewee (Gläser and Laudel, 2010, p. 42). The subsequent extraction and summarization of the data were carried out by following the procedure of

Mayring (1994) and based on a literal transcript. The Citavi 6 software was used to code and qualitatively analyze all corresponding modularization effects.

### **Step 3: Focus group**

The focus group is a moderated, mostly guideline-based discourse process in which a small group of six to twelve people is encouraged to discuss a specific topic by an information input from the researcher. The goal in the course of this group interaction is to collect data, whereby as many different aspects of a topic as possible are to be illuminated (Schulz, 2012, pp. 9–13). Usually, focus groups are not used as a separate method in the research process but are rather integrated into multi-method designs, as is the case in this paper. Nevertheless, the advantages of the interview, such as deeper insights into the experience of the respondents, should not be overlooked. According to Schulz (2012, p. 12), a combination of the two research methods is worthwhile. Therefore, semi-structured interviews and a focus group were applied in this article.

The focus group took place in the format of a one-day workshop after the expert interviews had been conducted and evaluated. The topics and questions of the expert interviews were used to initiate the discussion within the focus group as the goal was to validate and expand the previous research results. There is no uniform procedure for the evaluation of focus groups (Schulz, 2012, p. 12). In this article, a literal transcript is prepared, which was evaluated analogously to the expert interviews using Citavi 6 software and the procedure of Mayring (1994).

#### **Step 4: Concept development**

In this step, the previously elaborated results are synthesized. For this purpose, the code structures of the SLR, the semi-structured expert interviews, and the focus group are merged. The result of the synthesis is a three-level pyramid, which hierarchically structures the effects. Based on this pyramid, the effects are allocated to the corresponding PLCP and SSF of a company. The detailed description of the three-level pyramid and its elements as well as the allocation of the effects to the PLCP and SSF take place in the results section of the article.

#### **Step 5: In-depth interview**

To validate the effect allocation to the appropriate PLCP and SSF, one in-depth interview has been conducted. In the literature, an in-depth interview is described as a rather unstructured and personal interview with a single respondent. The aim is to reveal in-depth views and assessments on a topic (Frankel, Naslund and Bolumole, 2005, p. 197). The in-depth interview started with a short presentation of the preliminary results and has been conducted at advanced stages of the research process. The in-depth interview lasted for 180 minutes. The validation refers to product modularization effects whose PLCP and SSF precise allocation was previously not possible due to insufficiently specific explanations in the literature and expert interviews or focus group.

### 3 A product life-cycle phase specific concept for effect allocation

By conducting a systematic literature search, 13 expert interviews and a focus group, a total of 249 modularization effects in integrated supply chains were identified. In the course of extracting the product modularization effects by coding, different effect levels have emerged. This is because some effects, according to the principle of a causal chain, cause the emergence of further effects.

The functional decoupling through reduction of function division and the physical decoupling of modules through interfaces were identified as "first-level effects" in the code structure. Those effects can be interpreted as basic elements of modular product architectures.

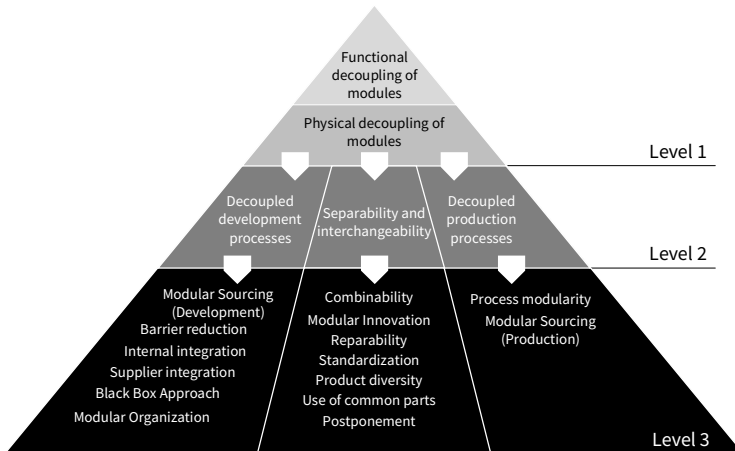


Figure 4: Systematical structure of the modularization effects

Product modularization results from the interaction of these two effects. Consequently, these first-level effects bundle all further modularization effects. In the next step some effects of the second code structure level were also categorized as "main effects" in order to create transparency and to highlight the most important ones. Those modularization effects that result from the effects of the first level and lead to more than ten further effects each were recorded as "main effects" of the second code structure level. These include the process-related effects of decoupling the development and production processes and the product-related effect of separability and interchangeability (of modules). These main effects are of correspondingly great importance, as they divide all other product modularization effects into three different dimensions.

The approach for highlighting main effects was also applied to all effects beyond the first two levels of the code structure, with the difference that these were categorized as main effects if they bundled more than five further sub-effects each. A total of 20 main effects could be identified through this procedure, of which 11 main effects are attributable to both research and practice. The remaining nine main effects could only be identified within the systematic literature search. Main effects that result exclusively from practice could not be identified. Figure 4 shows a pyramid that structures all identified main effects systematically.

The allocation of the effects to the appropriate PLCP and SSF is based on the 249 identified modularization effects and its expected impacts stated in the literature and expert interviews (or focus group). Every effect was assigned to exactly one PLCP/SSF combination. The result can be seen in Figure 5. A distinction is made between positive (+1) and negative (-1) effects. The allocation of product modularization effects was discussed in the in-

depth interview and adjusted at relevant points. This refers to the effects whose precise allocation was previously not possible due to insufficiently specific explanations in the literature and expert interviews (or focus group).

In the following part, the elaborated 20 main effects which cause the shown impacts on the PLCP are described in detail.



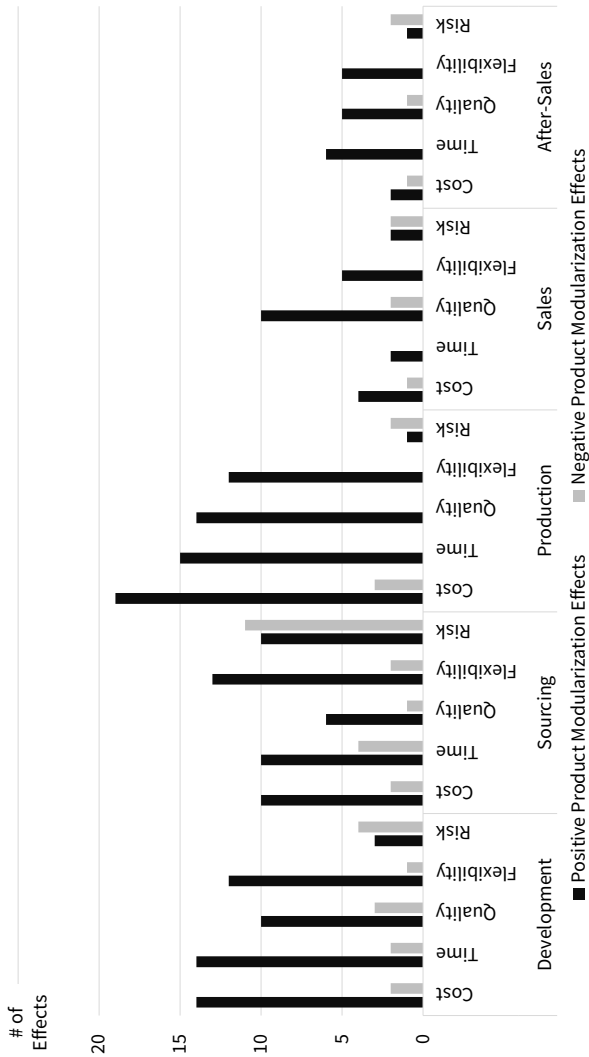


Figure 5: Effect allocation

## **Functional decoupling of modules**

Functional decoupling refers to the reduction of the functional division of components or modules and the resulting independence of modules. Due to the intended 1-to-1 mapping of components (modules) to functions, components (modules) fulfill fewer functions in modular product architectures compared to the integral design. The resulting sub-effects relate to changes in product structure or complexity (Ulrich, 1995, p. 422).

## **Physical decoupling of modules**

Interface definition and standardization creates physical independence from modules by defining decouplable or reversible interfaces (Ulrich, 1995, p. 422). This ensures that the connections between the components within a module remain powerful, while the connections between the modules are relatively weak. The standardization of interfaces across different products or product families or even company boundaries represents the second step, which reinforces the potential of product modularization (Sanchez and Mahoney, 1996, pp. 65–66). As described, physical decoupling allows exploiting the three main effects of "separability or exchangeability", "decoupling of development processes", and "decoupling of production processes", whereby it must be mentioned that these are partly created by the interplay between functional and physical decoupling. Since the literature focuses primarily on physical separability when mentioning the main effects, they are mostly attributed to the main effect of physical decoupling of modules. In this way, a double inclusion of the subordinate main effects as well as their sub-effects could be avoided in the evaluation of the effects on the PLCP.

## **Decoupled development processes**

When the view changes from the modular product to the processes of the modularizing company, the decoupling of development processes can be determined. The decoupling of development processes refers to the possibility of separate and parallel development, which arises when the functions of modules are precisely specified and the interfaces between individual modules and the rest of the product are fully defined. The possibility of decoupling processes results from the functional and physical independence of modules (Sanchez and Mahoney, 1996, p. 64) (Danese and Filippini, 2010, p. 1194). Thus, the coordination of processes can be limited to ensure that the components or modules to be developed correspond to the standardized interfaces (Ulrich, 1994, p. 224). Product development can be divided internally and externally by having different development teams taking over the development of individual modules (Vickery, et al., 2016, p. 755).

## **Separability and interchangeability**

As can already be seen from the explanations above, product modularization results in a decoupling of modules within a product architecture. This decoupling can be transformed into a relatively simple separability of the individual modules. Moreover, in addition to this reversibility, other modules can be easily inserted into the product architecture (interchangeability), if standardization of the corresponding interface is assumed (Fixson, 2005, p. 359) (Sanchez and Mahoney, 1996, pp. 65–66). The primary effects

of separability and interchangeability are increased combinability, modular innovation, and reparability. These effects will be discussed in detail later.

### **Decoupled production processes**

Parallel to the decoupling of the development processes, the division of a product into independent modules also enables the decoupling of production processes according to the same principle. Accordingly, the production of the individual modules or subsystems can be carried out independently of each other and parallel to each other, internally and externally, in different plants (Ulrich, 1994, p. 224) (Pashaei and Olhager, 2017, p. 362).

### **Modular sourcing (Development)**

According to Christensen (2011, p. 214), the more efficient coordination in integrating suppliers is reflected in the sourcing of development and production activities. Here, favorable framework conditions are created by combining individual parts into complete functional units (modules) within the framework of "modular sourcing", which are developed, manufactured and pre-assembled by module suppliers before being delivered to the final assembly plants. The possibility of modular sourcing also results due to the independence of individual modules from the rest of the product architecture (Wang and Zhang, 2019, p. 11). Modular sourcing is separated into the spin-off of development activities on the one hand and production activities on the other. These are described at a later stage below.

## **Barrier reduction**

At the beginning of this section, it should be mentioned that within this article no difference is made between different degrees of modularity, but a discrete way of thinking in integral and modular product architectures is assumed. This is of importance since different views dominate in the literature regarding the characteristics of information sharing and the resulting type of supply chain collaboration. According to Howard and Squire (2007), a modular product architecture leads to increased information sharing between buyers and suppliers, from initial design to delivery. This, in turn, leads to increased supply chain collaboration and information sharing.

In contrast, Cammarano, Michelino and Caputo (2019, p. 2) for example, do not make a direct distinction between degrees of modularity and take a much more radical stance by considering modularization and collaboration as opposites. Nevertheless, they do not exclude the integration of suppliers but argue that it is achieved by coordination through standardized interfaces. This means that the cooperative technical development of components or modules between the buyer and suppliers can be minimized as far as possible and handled almost completely autonomously by one of the two parties. Only initial contents such as specifications and communication channels must be defined together in advance. Therefore, the essential requirement to be met is the installment of components or modules with a specific function within the product architecture of the buyer via standardized interfaces.

At the same time, it should be mentioned that the occurrence of completely modular product architectures is rather unlikely (Ulrich, 1995, p. 424). Nevertheless, this idealized view serves to illustrate the maximum potential of

product modularity and is therefore suitable for achieving the goals of this article.

Beyond the discussion on the degree of collaboration between buyers and suppliers, a modular product architecture leads to the establishment of a "common language" which simplifies the way a product is described. This also simplifies communication and information flow between the various internal and external business units (Lorenzi and Di Lello, 2001, p. 432). This leads to the dismantling of internal and external communication barriers, thus promoting both supplier and internal integration (Boer and Boer, 2019) (Seyoum and Lian, 2018, p. 857). These subordinate main effects are described below.

### **Internal integration**

Internal integration refers to teamwork and the participation of different internal departments and functions in decision-making, which is increasingly taking place in the context of product modularization (Wang and Zhang, 2019, p. 2). Zhang, et al. (2019), were also able to demonstrate the positive effects of product modularization on internal quality integration. They define internal quality integration as the degree to which an organization structures its policies, practices and procedures into collaborative, synchronized processes to meet the quality requirements of its customers (Zhang, et al., 2019, p. 7). In doing so, they include quality aspects related to production, development and sales processes in their approach (Zhang, et al., 2019, p. 10).

## **Supplier integration**

The term supplier integration can be derived from the definition of supply chain integration, which is described overall as a process of redefining and connecting units or companies through the coordination or exchange of information and resources (Mujuni Katunzi, 2011, p. 106). Supplier integration suggests that suppliers provide information and participate in decision-making. It is characterized by a cooperative relationship between the buyer and the upstream supplier (Petersen, Handfield and Ragatz, 2005, p. 379). Modular product architecture enriches supplier integration by reducing the complexity of communication and interaction with suppliers as far as possible to the interfaces of a module, thus enabling efficient coordination (Seyoum and Lian, 2018, p. 857) (Wang and Zhang, 2019, p. 5). Accordingly, more efficient supplier integration results as a positive effect of modular product architecture compared to integral product architecture.

## **Black box approach**

Two different alternatives to the black box approach have been identified in the literature. The original black box approach represents a radical mechanism compared to supplier integration, where product development is split between a buyer and supplier, with the buyer only defining the basic requirements in terms of design, cost and interface details and transferring the responsibility for delivering the detailed component design, prototyping and production to the supplier. The supplier thus follows the rough framework conditions set by the buyer (Clark, et al., 1987, p.741). In connection with modular products, Cammarano, Michelino and Caputo (2019,

pp. 2–4), go one step further and expand this approach by describing an autonomous component or module development by the supplier. In doing so, suppliers develop independent innovations and invest heavily in standardized interfaces that enable embedded coordination, while the buyer has to adapt his activities to the supplier's interfaces to effectively integrate the component or module innovation into products. Basically, in both variants of the black box approach, the interface is predefined by one of the two parties, while the other party must align accordingly. This is the main difference to the more "classic" integration mechanisms, where the interfaces and the design are usually developed or adapted together (Cammarano, Michelino and Caputo, 2019, pp. 2–4).

### **Modular organization**

The theory of the emergence of modular organizations in the course of product modularization originally comes from Sanchez and Mahoney (1996, p. 73), who argue that modular product architectures not only create flexible product designs but also cause the design of loosely coupled, flexible, "modular" organizational structures. The main reason for this is that coordination is embedded in fully specified and standardized component interfaces, which eliminate the need to exercise management authority. If the coordination between buyers and suppliers can be concentrated and reduced to the standardized interfaces, except for possible initial coordination, this results in a reduced need for coordination and collaboration. This increased degree of autonomy means that suppliers can be kept at a certain distance.



## **Combinability**

Combinability results from the fact that modular product architectures create flexible product designs through the interchangeability of individual modules. This implies the possibility of a cross-product "mix and match" of different modules, with standardized interfaces, which can result in new variants (Sanchez, 1995, p. 143).

## **Modular innovation**

Modular innovation refers to the ability to upgrade a product by replacing individual, "obsolete" modules with new, technically more sophisticated modules without affecting the rest of the product structure. This ability is given to modular product architectures by the independence of individual modules as well as the resulting easy interchangeability (Danese and Filippini, 2010, p. 1194).

## **Reparability**

The simplified reparability of modular products compared to integral ones is also made possible by the separability of the individual modules. This allows problems within the product to be identified more quickly (Lau, Yam and Tang, 2007, p. 1053). In addition, the increased exchangeability can lead to a simple replacement of defective modules according to the "plug & play" principle, whereby a disassembly of the entire product or system could be avoided (Droge, Vickery and Jacobs, 2012, p. 253).

## **Standardization**

Because of their combinability, a standardization of modules and components across the product families of a company is encouraged (Zhang, Zhao and Qi, 2014, p. 147). This standardization is possible because the functions of a component or module in the modular design are clearly defined and physically separable. Also, random interactions between a component or module and the rest of the product are minimized. This simplifies the integration of a module within different products if a standardized interface is used (Ulrich, 1994, p. 223). In addition, standardization supports increased use of common parts and postponement capability.

## **Product diversity**

The combinability leads to the fact that through "mix and match", companies can create a significantly higher product variety from a relatively small number of different components (Ulrich, 1994, pp. 223–224).

## **Use of common parts**

The use of common parts is promoted by the fact that standardization enables the effective use of modules in several variants of a product family or over several product generations. The reuse of modules also requires increased use of common parts (Fixson and Clark, 2002, p. 135) (Kohr, Budde and Friedli, 2017, p. 57) (interview 8, minute 55).

## **Postponement**

The postponement strategy refers to the late, customer-specific differentiation of a standard product into different variants. Modularization allows a

company to maximize the number of standard components and assemble these components for all possible product options in the earlier stages of the assembly process. The addition of components that differentiate the product from others can be shifted to the later stages of the production process (Feitzinger and Hau, 1997, p. 117).

### **Process modularity**

The understanding of process modularity in the context of this article results from the definition of Tu, et al. (2004, p. 151), who interpret it as the standardization of process modules in production, whereby processes can be rearranged or new process modules added promptly in response to changing product requirements.

### **Modular Sourcing (Production)**

The modular sourcing of production activities follows the same principle as the modular sourcing of development activities described above. Accordingly, a separate description of the effect is not given here, and reference is made to the above explanations on modular sourcing of development activities.

## 4 Results

This section of the article answers the following research questions:

- 1) Which product life-cycle phase (PLCP) specific product modularization effects result from supply chain integration in the drive technology industry?
- 2) How do those effects affect the strategic success factors (SSF) of a company in the drive technology industry?

To be able to present the cost-oriented effects of product modularization on the PLCP transparently, an allocation to the corresponding PLCP and SSF was carried out. An overall view of the product modularization effects on the PLCP has been created by summarizing all the effects per main effect all the way up to the original effects of functional and physical decoupling. Looking exclusively at the effects of product modularization within each PLCP, it is shown that opportunities arise primarily in the development, procurement, and production phases. Especially in the production phase, many positive effects can be assumed with minimal negative influences. In the sales and after-sales phases, on the other hand, meaningfully fewer positive effects were observed, although a clear predominance of positive effects in relation to the negative effects can be observed here too.

If the perspective changes to the effects of product modularization on SSF, there is an almost balanced allocation of effects on cost, time, quality, and flexibility. This applies to both the positive and negative effects. From this, it can be deduced that companies with different strategic orientations can benefit from product modularization. Only the SSF risk shows a surplus of

negative effects, that mainly occur in the procurement phase. These negative effects, however, mostly represent potential influences that can be prevented or shifted to other locations by using appropriate approaches.

## 5 Conclusion

A total of 249 effects of product modularization have been identified, of which 174 were identified from research, 31 from practice, and 44 from both perspectives. Due to the bundeling of a large number of (sub-)effects, 20 of these effects with a correspondingly central character could be highlighted as so-called main effects. The basic elements of functional and physical decoupling of components or modules as well as the standardization of the corresponding interfaces were identified as the origin of all effects. On the second main effect level, the product-related separability and interchangeability, as well as the process-related effects of decoupled development and production activities, have been identified.

### 5.1 Managerial implications

The main difference between the research and the practical perspective lies in the product-related and the process-related effects. While practitioners focus largely on the product-related effects of product modularization, the process-related effects are neglected. Researchers follow a more holistic perspective, from which it is possible to deduce that the potential of product modularization in the drive technology industry has not yet been fully exploited. It turns out that the possibilities for the integration of suppliers resulting from the decoupling of development and production processes have not yet been exploited in practice. It should be mentioned that the positive effects in this area are associated with a high degree of modularity. Also, the main effects of the development and production process decoupling cause the most negative effects, especially in the procurement phase. For these reasons, the current neglect of the effects of the development and

production process decoupling could be explained. Nevertheless, a considerable potential could be demonstrated by these effects, which should compensate for the negative effects of an adequate implementation of product modularization. Consequently, the stronger consideration of the process-related effect dimensions as well as the resulting consequential effects can be derived as a recommendation for action in practice. Besides, the effects associated with product-related separability and interchangeability, such as improved combinability, standardization, product variety, or the enabling of modular innovation, have been identified both in research and in practice. Those effects generate the greatest amount of positive impacts, especially in regard to the conflict between individualization and standardization of products. Negative effects, on the other hand, appear to be strongly neglected both in research and practice. A possible reason for this could be the bias of many researchers and the experts interviewed, who would like to present product modularization as a suitable solution for mastering the increasing complexity in companies and accordingly focus the positive effects stronger than the negative ones.

## **5.2 Further research**

All in all, the current state of research and practice on the maximum potential of product modularization was compiled in both positive and negative aspects. A considerable surplus of positive effects on the PLCP could be identified. Since the effects within this article explicitly represent potentials, some of which can only be generated under certain circumstances, all effects must be individually related to the respective company. This could reduce the shown maximum potential of product modularization because the fulfillment of all conditions is considered unlikely. This also applies to

the negative effects, the extent of which should also be evaluated individually.



## Appendix

### Appendix 1: Relevant publications

#	Authors	Object of investigation
1	Chanaron, 2001	
2	Des Doran, 2002	
3	Hoetker, Swaminathan and Mitchell, 2007	
4	Howard and Squire, 2007	Buyer-Supplier-Relationship
5	Cabigiosu and Camuffo, 2012	
6	Squire, et al., 2009	
7	Furlan, Cabigiosu and Camuffo, 2014	
8	Pero, et al., 2018	
9	Sanchez and Mahoney, 1996	Modular Organization
10	Hoetker, 2006	

#	Authors	Object of investigation
11	Ulrich, 1994	Product design / architecture
12	Ulrich, 1995	Product design / architecture
13	Fixson and Clark, 2002	
14	Fixson, 2005	Product design / architecture
15	Fixson, 2007	
16	Doran and Hill, 2009	
17	Pil and Cohen, 2006	
18	Jin and Zong, 2012	
19	Bouncken, Pesch and Gudergan, 2015	New Product Development and Innovation
20	Xue-feng and Yan-xia, 2013	
21	Vos, et al., 2018	

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#	Authors	Object of investigation
22	Cammarano, Michelino and Caputo, 2019	
23	Hsiao, Tan and Chiou, 2019	
24	Arnheiter and Harren, 2005	
25	Takahiro and Dongsheng, 2006	
26	Abdelkafi, Blecker and Pero, 2010	
27	Danese and Filippini, 2010	New Product Development and Innovation
28	Huang, Stewart and Le Chen, 2010	
29	Pero, et al., 2010	
30	Christensen, 2011	
31	Parente, Baack and Hahn, 2011	
32	Danese and Filippini, 2013	

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#	Authors	Object of investigation
33	Ye, et al., 2018	
34	Vickery, et al., 2016	New Product Development and Innovation
35	Arora, Gambardella and Rullani, 1997	
36	Novak and Eppinger, 2001	Supply Chain Integration
37	Hsuan Mikkola and Skjøtt-Larsen, 2004	
38	Lau, Yam and Tang, 2007	
39	Droge, Vickery and Jacobs, 2012	
40	Davies and Joglekar, 2013	
41	Zhou, Gu and Yuan, 2014	Supply Chain Integration
42	Sorkun, 2016	
43	Wang and Zhang, 2019	

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#	Authors	Object of investigation
44	Zhang, et al., 2019	
45	C. Y. Baldwin and K. B. Clark, 1997	
46	Christensen, Raynor and Verlinden, 2001	
47	Bask, et al., 2010	Implementation / Management
48	Minartz, 2010	
49	Skirde, Kersten and Schröder, 2016	
50	Kohr, Budde and Friedli, 2017	
51	van Hoek and Weken, 1998	Supply Chain Architektur
52	Lorenzi and Di Lello, 2001	
53	Doran, 2003b	Supply Chain Architektur
54	Doran, 2003a	

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#	Authors	Object of investigation
56	Lau and Yam, 2005	
57	Ro, Liker and Fixson, 2007	
58	Zirpoli and Camuffo, 2009	Supply Chain Architektur
59	Pashaei and Olhager, 2017	
60	Sanchez and Hang, 2017	
61	Lin, 2003	
62	Lin, 2004	Supply Chain Performance
63	Bush, Tiwana and Rai, 2010	
64	Oh and Rhee, 2010	
65	Pashaei and Olhager, 2015	Supply Chain Performance
66	Rezk, Singh Srail and Williamson, 2016	

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#	Authors	Object of investigation
55	Doran, 2005	
67	Seyoum and Lian, 2018	Supply Chain Performance
68	Suh and Lee, 2018	
69	Gualandris and Kalchschmidt, 2013	
70	Gualandris and Kalchschmidt, 2015	Supply Chain Risk Management
71	Ciccullo, Pero and Caridi, 2017	
72	Feitzinger and Hau, 1997	
73	Liao, Deng and Marsillac, 2013	Mass Customization
74	Zhang, Zhao and Qi, 2014	
75	Sanchez, 1995	Company performance
76	Worren, Moore and Cardona, 2002	

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#	Authors	Object of investigation
77	Jacobs, Vickery and Droge, 2007	
78	Eidelwein, et al., 2018	
79	Wurzer and Reiner, 2018	
80	Boer and Boer, 2019	Company performance
81	Mee-ngoen, Thongrawd and Jemsittiparsert, 2019	
82	Saeed, Malhotra and Abdinnour, 2019	
83	Pashaei and Olhager, 2019	
84	Fernández and Kekäle, 2005	
86	Durand, Telenko and Seepersad, 2010	Reverse Logistics & Sustainability
87	Sonego, Echeveste and Galvan Debarba, 2018	



## Appendix 2: Participants of the empirical study

#	Supply Chain Stage	Function	Inter-view	Focus Group	In-Depth Inter-view
1	Module supplier	HO Development	X	X	
2	Module supplier	Controller	X		
3	Component and module supplier	HO Development	X		
4	System supplier	Resource Manager	X	X	
5	Component and module supplier	HO Modularization	X	X	
6	Component and module supplier	Project Manager	X		
7	System supplier	HO Controlling	X	X	
8	System supplier	HO Controlling	X	X	
9	System supplier	HO Development	X		
10	Consulting	Project Manager	X		X

#	Supply Stage	Chain	Function	Inter-view	Focus Group	In-Depth Interview
11	System supplier		HO Control- ling	X		
12	System supplier		HO Control- ling	X	X	
13	Component supplier		Complexity Manager	X		

## References

- Abdelkafi, N., Blecker, T. and Pero, M., 2010. Aligning New Product Development and Supply Chains: Development of a Theoretical Framework and Analysis of Case Studies. In: J. Kacprzyk, G. Q. Huang, K. L. Mak, and P. G. Maropoulos, eds. 2010. Proceedings of the 6th CIRP-Sponsored International Conference on Digital Enterprise Technology. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 1399–1419.
- Arnheiter, E. D. and Harren, H., 2005. A typology to unleash the potential of modularity. *Journal of Manufacturing Technology Management*, [e-journal] 16(7), pp. 699–711. <http://dx.doi.org/10.1108/17410380510619923>.
- Arora, A., Gambardella, A. and Rullani, E., 1997. Division of labour and the locus of inventive activity. *Journal of Management & Governance*, [e-journal] 1(1), pp. 123–140. <http://dx.doi.org/10.1023/A:1009993430964>.
- Bask, A., Lipponen, M., Rajahonka, M. and Tinnilä, M., 2010. The concept of modularity: diffusion from manufacturing to service production. *Journal of Manufacturing Technology Management*, [e-journal] 21(3), pp. 355–375. <http://dx.doi.org/10.1108/17410381011024331>.
- Boer, H. and Boer, H., 2019. Design-for-variety and operational performance. *Journal of Manufacturing Technology Management*, [e-journal] 30(2), pp. 438–461. <http://dx.doi.org/10.1108/JMTM-03-2018-0065>.
- Bouncken, R. B., Pesch, R. and Gudergan, S. P., 2015. Strategic embeddedness of modularity in alliances: Innovation and performance implications. *Journal of Business Research*, [e-journal] 68(7), pp. 1388–1394. <http://dx.doi.org/10.1016/j.jbusres.2015.01.020>.
- Bush, A. A., Tiwana, A. and Rai, A., 2010. Complementarities Between Product Design Modularity and IT Infrastructure Flexibility in IT-Enabled Supply Chains. *IEEE Transactions on Engineering Management*, [e-journal] 57(2), pp. 240–254. <http://dx.doi.org/10.1109/TEM.2010.2040741>.
- C. Y. Baldwin and K. B. Clark, 1997. Managing in an Age of Modularity. *Harvard Business Review*, 75(5), pp. 84–93.

- Cabigiosu, A. and Camuffo, A., 2012. Beyond the “Mirroring” Hypothesis: Product Modularity and Interorganizational Relations in the Air Conditioning Industry. *Organization Science*, [e-journal] 23(3), pp. 686–703. <http://dx.doi.org/10.1287/orsc.1110.0655>.
- Cammarano, A., Michelino, F. and Caputo, M., 2019. The purchase of innovative components as an open innovation practice: redefining the boundaries between closed and open innovation. In: . 2019. 2019 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC): IEEE, pp. 1–9.
- Chanaron, J. J., 2001. Implementing technological and organisational innovations and management of core competencies: lessons from the automotive industry. *International Journal of Automotive Technology and Management*, [e-journal] 1(1), p. 128–128. <http://dx.doi.org/10.1504/IJATM.2001.000031>.
- Christensen, C. M., Raynor, M. and Verlinden, M., 2001. Skate to where the money will be. *Harvard Business Review*, (79), pp. 72–80.
- Christensen, T. B., 2011. Modularised eco-innovation in the auto industry. *Journal of Cleaner Production*, [e-journal] 19(2-3), pp. 212–220. <http://dx.doi.org/10.1016/j.jclepro.2010.09.015>.
- Ciccullo, F., Pero, M. and Caridi, M., 2017. Exploring the hidden potential of product design to mitigate supply chain risk. *International Journal of Electronic Customer Relationship Management*, [e-journal] 11(1), p. 66–66. <http://dx.doi.org/10.1504/IJECRM.2017.086753>.
- Clark, K. B., Chew, W. B., Fujimoto, T., Meyer, J. and Scherer, F. M., 1987. Product Development in the World Auto Industry. *Brookings Papers on Economic Activity*, [e-journal] 1987(3), p. 729–729. <http://dx.doi.org/10.2307/2534453>.
- Cook, D. J., Mulrow, C. D. and Haynes, R. B., 1997. Systematic reviews: synthesis of best evidence for clinical decisions. *Annals of internal medicine*, [e-journal] 126(5), pp. 376–380. <http://dx.doi.org/10.7326/0003-4819-126-5-199703010-00006>.
- Danese, P. and Filippini, R., 2010. Modularity and the impact on new product development time performance. *International Journal of Operations & Production Management*, [e-journal] 30(11), pp. 1191–1209. <http://dx.doi.org/10.1108/01443571011087387>.

- Danese, P. and Filippini, R., 2013. Direct and Mediated Effects of Product Modularity on Development Time and Product Performance. *IEEE Transactions on Engineering Management*, [e-journal] 60(2), pp. 260–271. <http://dx.doi.org/10.1109/TEM.2012.2208268>.
- Davies, J. and Joglekar, N., 2013. Supply Chain Integration, Product Modularity, and Market Valuation: Evidence from the Solar Energy Industry. *Production and Operations Management*, [e-journal] 22(6), pp. 1494–1508. <http://dx.doi.org/10.1111/poms.12052>.
- Des Doran, 2002. Manufacturing for synchronous supply: a case study of Ikeda Hoover Ltd. *Integrated Manufacturing Systems*, [e-journal] 13(1), pp. 18–24. <http://dx.doi.org/10.1108/09576060210411477>.
- Doran, D., 2003a. An evaluation of value-transfer within a modular supply chain. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 217(7), pp. 521–527.
- Doran, D., 2003b. Supply chain implications of modularization. *International Journal of Operations & Production Management*, [e-journal] 23(3), pp. 316–326. <http://dx.doi.org/10.1108/01443570310462785>.
- Doran, D., 2005. Supplying on a modular basis: an examination of strategic issues. *International Journal of Physical Distribution & Logistics Management*, [e-journal] 35(9), pp. 654–663. <http://dx.doi.org/10.1108/09600030510632023>.
- Doran, D. and Hill, A., 2009. A review of modular strategies and architecture within manufacturing operations. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, [e-journal] 223(1), pp. 65–75. <http://dx.doi.org/10.1243/09544070JAUTO822>.
- Droge, C., Vickery, S. K. and Jacobs, M. A., 2012. Does supply chain integration mediate the relationships between product/process strategy and service performance? An empirical study. *International Journal of Production Economics*, [e-journal] 137(2), pp. 250–262. <http://dx.doi.org/10.1016/j.ijpe.2012.02.005>.
- Durand, J., Telenko, C. and Seepersad, C., 2010. How Does Modularity Affect Green Design? In: . 2010. Volume 6: 15th Design for Manufacturing and the Lifecycle Conference; 7th Symposium on International Design and Design Education: AS-MEDC, pp. 405–415.

- Eidelwein, F., Piran, F. A. S., Lacerda, D. P., Dresch, A. and Rodrigues, L. H., 2018. Exploratory Analysis of Modularization Strategy Based on the Theory of Constraints Thinking Process. *Global Journal of Flexible Systems Management*, [e-journal] 19(2), pp. 111–122. <http://dx.doi.org/10.1007/s40171-017-0177-1>.
- Feitzinger, E. and Hau, L. L., 1997. Mass customization at Hewlett-Packard: the power of postponement. *Harvard Business Review*, (75), pp. 116–123.
- Fernández, I. and Kekäle, T., 2005. The influence of modularity and industry clock-speed on reverse logistics strategy: Implications for the purchasing function. *Journal of Purchasing and Supply Management*, [e-journal] 11(4), pp. 193–205. <http://dx.doi.org/10.1016/j.pursup.2006.01.005>.
- Fixson, S. K., 2005. Product architecture assessment: a tool to link product, process, and supply chain design decisions. *Journal of Operations Management*, [e-journal] 23(3-4), pp. 345–369. <http://dx.doi.org/10.1016/j.jom.2004.08.006>.
- Fixson, S. K., 2007. Modularity and Commonality Research: Past Developments and Future Opportunities. *Concurrent Engineering*, [e-journal] 15(2), pp. 85–111. <http://dx.doi.org/10.1177/1063293X07078935>.
- Fixson, S. K. and Clark, J. P., 2002. On the link between modularity and cost—a methodology to assess cost implications of product architecture differences. In: . 2002. *IEEE International Engineering Management Conference: IEEE*, pp. 131–136.
- Frankel, R., Naslund, D. and Bolumole, Y., 2005. The “White Space” of Logistics Research: A Look at the Role of Methods Usage. *Journal of Business Logistics*, [e-journal] 26(2), pp. 185–209. <http://dx.doi.org/10.1002/j.2158-1592.2005.tb00211.x>.
- Furlan, A., Cabigiosu, A. and Camuffo, A., 2014. When the mirror gets misted up: Modularity and technological change. *Strategic Management Journal*, [e-journal] 35(6), pp. 789–807. <http://dx.doi.org/10.1002/smj.2138>.

- Gläser, J. and Laudel, G., 2010. Experteninterviews und qualitative Inhaltsanalyse als Instrumente rekonstruierender Untersuchungen. 4th ed. [e-book]. Wiesbaden: VS Verlag. Available at: Gläser, Jochen (VerfasserIn)  
Laudel, Grit (VerfasserIn)  
Gläser, Jochen (VerfasserIn)  
Laudel, Grit (VerfasserIn). <<http://d-nb.info/1002141753/04>>.
- Gualandris, J. and Kalchschmidt, M., 2013. Product and process modularity: improving flexibility and reducing supplier failure risk. *International Journal of Production Research*, [e-journal] 51(19), pp. 5757–5770.  
<http://dx.doi.org/10.1080/00207543.2013.793430>.
- Gualandris, J. and Kalchschmidt, M., 2015. Mitigating the effect of risk conditions on supply disruptions: the role of manufacturing postponement enablers. *Production Planning & Control*, [e-journal] 26(8), pp. 637–653.  
<http://dx.doi.org/10.1080/09537287.2014.955895>.
- Hoetker, G., 2006. Do modular products lead to modular organizations? *Strategic Management Journal*, [e-journal] 27(6), pp. 501–518.  
<http://dx.doi.org/10.1002/smj.528>.
- Hoetker, G., Swaminathan, A. and Mitchell, W., 2007. Modularity and the Impact of Buyer–Supplier Relationships on the Survival of Suppliers. *Management Science*, [e-journal] 53(2), pp. 178–191. <http://dx.doi.org/10.1287/mnsc.1060.0630>.
- Howard, M. and Squire, B., 2007. Modularization and the impact on supply relationships. *International Journal of Operations & Production Management*, [e-journal] 27(11), pp. 1192–1212. <http://dx.doi.org/10.1108/01443570710830593>.
- Hsiao, C.-C., Tan, D. and Chiou, J.-S., 2019. Electronic integration and capability widening for OEM suppliers. *International Marketing Review*, [e-journal] ahead-of-print(ahead-of-print). <http://dx.doi.org/10.1108/IMR-02-2018-0071>.
- Hsuan Mikkola, J. and Skjøtt-Larsen, T., 2004. Supply-chain integration: implications for mass customization, modularization and postponement strategies. *Production Planning & Control*, [e-journal] 15(4), pp. 352–361.  
<http://dx.doi.org/10.1080/0953728042000238845>.

- Huang, T.-T. A., Stewart, R. A. and Le Chen, 2010. Identifying key enablers to improve business performance in Taiwanese electronic manufacturing companies. *International Journal of Operations & Production Management*, [e-journal] 30(2), pp. 155–180. <http://dx.doi.org/10.1108/01443571011018699>.
- Jacobs, M., Vickery, S. K. and Droge, C., 2007. The effects of product modularity on competitive performance. *International Journal of Operations & Production Management*, [e-journal] 27(10), pp. 1046–1068. <http://dx.doi.org/10.1108/01443570710820620>.
- Jin, Z.-k. and Zong, Y.-z., 2012. The effects of modular production on the module suppliers' willingness to innovate. In: . 2012. 2012 International Conference on Management Science & Engineering 19th Annual Conference Proceedings: IEEE, pp. 651–657.
- Kersten, W., Lammers, T. and Skride, H., 2011. Entwicklung eines Kriterienkataloges zur strukturierten Allokation von Effekten der Modularisierung, pp. 14–30.
- Kohr, D., Budde, L. and Friedli, T., 2017. Identifying Complexity Drivers in Discrete Manufacturing and Process Industry. *Procedia CIRP*, [e-journal] 63, pp. 52–57. <http://dx.doi.org/10.1016/j.procir.2017.03.290>.
- Lau, A. K.W., Yam, R. C.M. and Tang, E. P.Y., 2007. Supply chain product co-development, product modularity and product performance. *Industrial Management & Data Systems*, [e-journal] 107(7), pp. 1036–1065. <http://dx.doi.org/10.1108/02635570710816739>.
- Lau, A.K.W. and Yam, R.C.M., 2005. A case study of product modularization on supply chain design and coordination in Hong Kong and China. *Journal of Manufacturing Technology Management*, [e-journal] 16(4), pp. 432–446. <http://dx.doi.org/10.1108/17410380510594516>.
- Liao, K., Deng, X. and Marsillac, E., 2013. Factors that influence Chinese automotive suppliers' mass customization capabilities. *International Journal of Production Economics*, [e-journal] 146(1), pp. 25–36. <http://dx.doi.org/10.1016/j.ijpe.2013.01.014>.



- Lin, B.-W., 2003. Cooperating for supply chain effectiveness: manufacturing strategy for Chinese OEMs. *International Journal of Manufacturing Technology and Management*, [e-journal] 5(3), p. 232–232. <http://dx.doi.org/10.1504/IJMTM.2003.003412>.
- Lin, B.-W., 2004. Original equipment manufacturers (OEM) manufacturing strategy for network innovation agility: the case of Taiwanese manufacturing networks. *International Journal of Production Research*, [e-journal] 42(5), pp. 943–957. <http://dx.doi.org/10.1080/00207540310001622449>.
- Lorenzi, S. and Di Lello, A., 2001. Product modularity theory and practice: the benefits and difficulties in implementation within a company. *International Journal of Automotive Technology and Management*, [e-journal] 1(4), p. 425–425. <http://dx.doi.org/10.1504/IJATM.2001.000050>.
- Mayring, P., 1994. Qualitative Inhaltsanalyse. In: A. Boehm, ed. 1994. *Texte verstehen. Konzepte, Methoden, Werkzeuge*. Konstanz: Univ.-Verl. Konstanz, pp. 159–175.
- Mee-ngoan, B., Thongrawd, C. and Jemsittiparsert, K., 2019. The impact of product and process strategies on the service performance: The mediating role of supply chain integrations. *International Journal of Supply Chain Management*, 8(4), pp. 291–301.
- Minartz, L., 2010. *Standardisierung von Schnittstellen im Rahmen der Produktmodularisierung - Entwicklung eines Kriterienkataloges zur Identifikation von Potenzialen am Beispiel von Antriebsachsen in der Landmaschinenindustrie*. Hamburg.
- Mujuni Katunzi, T., 2011. Obstacles to Process Integration along the Supply Chain: Manufacturing Firms Perspective. *International Journal of Business and Management*, [e-journal] 6(5). <http://dx.doi.org/10.5539/ijbm.v6n5p105>.
- Mulrow, C. D., 1994. Rationale for systematic reviews. *BMJ (Clinical research ed.)*, [e-journal] 309(6954), pp. 597–599. <http://dx.doi.org/10.1136/bmj.309.6954.597>.
- Novak, S. and Eppinger, S. D., 2001. Sourcing By Design: Product Complexity and the Supply Chain. *Management Science*, [e-journal] 47(1), pp. 189–204. <http://dx.doi.org/10.1287/mnsc.47.1.189.10662>.

- Oh, J. and Rhee, S.-K., 2010. Influences of supplier capabilities and collaboration in new car development on competitive advantage of carmakers. *Management Decision*, [e-journal] 48(5), pp. 756–774.  
<http://dx.doi.org/10.1108/00251741011043911>.
- Parente, R. C., Baack, D. W. and Hahn, E. D., 2011. The effect of supply chain integration, modular production, and cultural distance on new product development: A dynamic capabilities approach. *Journal of International Management*, [e-journal] 17(4), pp. 278–290. <http://dx.doi.org/10.1016/j.intman.2011.08.001>.
- Pashaei, S. and Olhager, J., 2015. Product architecture and supply chain design: a systematic review and research agenda. *Supply Chain Management: An International Journal*, [e-journal] 20(1), pp. 98–112. <http://dx.doi.org/10.1108/SCM-12-2013-0487>.
- Pashaei, S. and Olhager, J., 2017. The impact of product architecture on global operations network design. *Journal of Manufacturing Technology Management*, [e-journal] 28(3), pp. 353–370. <http://dx.doi.org/10.1108/JMTM-11-2015-0108>.
- Pashaei, S. and Olhager, J., 2019. Product architecture, global operations networks, and operational performance: an exploratory study. *Production Planning & Control*, [e-journal] 30(2-3), pp. 149–162.  
<http://dx.doi.org/10.1080/09537287.2018.1534267>.
- Pero, M., Abdelkafi, N., Sianesi, A. and Blecker, T., 2010. A framework for the alignment of new product development and supply chains. *Supply Chain Management: An International Journal*, [e-journal] 15(2), pp. 115–128.  
<http://dx.doi.org/10.1108/13598541011028723>.
- Pero, M., Micheli, G., Aiolfi, S. and Pacchiani, D., 2018. Triadic relationships in new product development: Contingent factors and implications for performance. In: . 2018. *Proceedings of the 23rd Summer School "Francesco Turco" - Industrial Systems Engineering 2018*, pp. 263–269.
- Petersen, K. J., Handfield, R. B. and Ragatz, G. L., 2005. Supplier integration into new product development: coordinating product, process and supply chain design. *Journal of Operations Management*, [e-journal] 23(3-4), pp. 371–388.  
<http://dx.doi.org/10.1016/j.jom.2004.07.009>.

- Pil, F. K. and Cohen, S. K., 2006. Modularity: Implications for Imitation, Innovation, and Sustained Advantage. *The Academy of Management Review*, [e-journal] 31(4), pp. 995–1011. <http://dx.doi.org/10.5465/amr.2006.22528166>.
- Rezk, R., Singh Srari, J. and Williamson, P. J., 2016. The impact of product attributes and emerging technologies on firms' international configuration. *Journal of International Business Studies*, [e-journal] 47(5), pp. 610–618. <http://dx.doi.org/10.1057/jibs.2016.9>.
- Ro, Y. K., Liker, J. K. and Fixson, S. K., 2007. Modularity as a Strategy for Supply Chain Coordination: The Case of U.S. Auto. *IEEE Transactions on Engineering Management*, [e-journal] 54(1), pp. 172–189. <http://dx.doi.org/10.1109/TEM.2006.889075>.
- Saeed, K. A., Malhotra, M. K. and Abdinnour, S., 2019. How supply chain architecture and product architecture impact firm performance: An empirical examination. *Journal of Purchasing and Supply Management*, [e-journal] 25(1), pp. 40–52. <http://dx.doi.org/10.1016/j.pursup.2018.02.003>.
- Sanchez, R., 1995. Strategic flexibility in product competition. *Strategic Management Journal*, [e-journal] 16(S1), pp. 135–159. <http://dx.doi.org/10.1002/smj.4250160921>.
- Sanchez, R. and Hang, C. C., 2017. Modularity in New Market Formation: Lessons for Technology and Economic Policy and Competence-Based Strategic Management. In: R. Sanchez, A. Heene, S. Polat, and U. Asan, eds. 2017. *Mid-Range Management Theory: Competence Perspectives on Modularity and Dynamic Capabilities*: Emerald Publishing Limited, pp. 131–165.
- Sanchez, R. and Mahoney, J. T., 1996. Modularity, flexibility, and knowledge management in product and organization design. *Strategic Management Journal*, [e-journal] 17(S2), pp. 63–76. <http://dx.doi.org/10.1002/smj.4250171107>.
- Schulz, M., 2012. Quick and easy!?! Fokusgruppen in der angewandten Sozialwissenschaft. In: M. Schulz, B. Mack, and O. Renn, eds. 2012. *Fokusgruppen in der empirischen Sozialwissenschaft. Von der Konzeption bis zur Auswertung*. Wiesbaden: Springer VS, pp. 9–22.

- Seyoum, B. and Lian, Y., 2018. Market performance implications of modularization: Evidence from global auto firms operating in China. *International Business Review*, [e-journal] 27(4), pp. 852–866.  
<http://dx.doi.org/10.1016/j.ibusrev.2018.01.008>.
- Skirde, H., Kersten, W. and Schröder, M., 2016. Measuring the Cost Effects of Modular Product Architectures — A Conceptual Approach. *International Journal of Innovation and Technology Management*, [e-journal] 13(04), p. 1650017–1650017.  
<http://dx.doi.org/10.1142/S0219877016500176>.
- Sonego, M., Echeveste, M. E. S. and Galvan Debarba, H., 2018. The role of modularity in sustainable design: A systematic review. *Journal of Cleaner Production*, [e-journal] 176, pp. 196–209. <http://dx.doi.org/10.1016/j.jclepro.2017.12.106>.
- Sorkun, M. F., 2016. Contrary evidence: product modularity and supplier integration. *International Journal of Integrated Supply Management*, [e-journal] 10(3/4), p. 283–283. <http://dx.doi.org/10.1504/IJISM.2016.081278>.
- Squire, B., Cousins, P. D., Lawson, B. and Brown, S., 2009. The effect of supplier manufacturing capabilities on buyer responsiveness. *International Journal of Operations & Production Management*, [e-journal] 29(8), pp. 766–788.  
<http://dx.doi.org/10.1108/01443570910977689>.
- Suh, C. J. and Lee, I. T., 2018. An Empirical Study on the Manufacturing Firm's Strategic Choice for Sustainability in SMEs. *Sustainability*, [e-journal] 10(3), p. 572–572. <http://dx.doi.org/10.3390/su10020572>.
- Takahiro, F. and Dongsheng, G., 2006. The architectural attributes of auto parts and transaction patterns on design drawings. *International Journal of Automotive Technology and Management*, [e-journal] 6(4), p. 370–370.  
<http://dx.doi.org/10.1504/IJATM.2006.012231>.
- Tranfield, D., Denyer, D. and Smart, P., 2003. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. *British Journal of Management*, [e-journal] 14(3), pp. 207–222.  
<http://dx.doi.org/10.1111/1467-8551.00375>.

- Tu, Q., Vonderembse, M. A., Ragu-Nathan, T. S. and Ragu-Nathan, B., 2004. Measuring Modularity-Based Manufacturing Practices and Their Impact on Mass Customization Capability: A Customer-Driven Perspective. *Decision Sciences, [e-journal]* 35(2), pp. 147–168. <http://dx.doi.org/10.1111/j.00117315.2004.02663.x>.
- Ulrich, K., 1994. Fundamentals of Product Modularity. In: S. Dasu, and C. Eastman, eds. 1994. *Management of Design*. Dordrecht: Springer Netherlands, pp. 219–231.
- Ulrich, K., 1995. The role of product architecture in the manufacturing firm. *Research Policy, [e-journal]* 24(3), pp. 419–440. [http://dx.doi.org/10.1016/0048-7333\(94\)00775-3](http://dx.doi.org/10.1016/0048-7333(94)00775-3).
- van Hoek, R. I. and Weken, H. A.M., 1998. The Impact of Modular Production on the Dynamics of Supply Chains. *The International Journal of Logistics Management, [e-journal]* 9(2), pp. 35–50. <http://dx.doi.org/10.1108/09574099810805825>.
- Vickery, S. K., Koufteros, X., Dröge, C. and Calantone, R., 2016. Product Modularity, Process Modularity, and New Product Introduction Performance: Does Complexity Matter? *Production and Operations Management, [e-journal]* 25(4), pp. 751–770. <http://dx.doi.org/10.1111/poms.12495>.
- Vos, M. A., Raassens, N., van der Borgh, M. and Nijssen, E. J., 2018. Balancing modularity and solution space freedom: effects on organisational learning and sustainable innovation. *International Journal of Production Research, [e-journal]* 56(20), pp. 6658–6677. <http://dx.doi.org/10.1080/00207543.2018.1458165>.
- Wang, Z. and Zhang, M., 2019. Linking product modularity to supply chain integration and flexibility. *Production Planning & Control*, pp. 1–15. <http://dx.doi.org/10.1080/09537287.2019.1700571>.
- Warren, N., Moore, K. and Cardona, P., 2002. Modularity, strategic flexibility, and firm performance: a study of the home appliance industry. *Strategic Management Journal, [e-journal]* 23(12), pp. 1123–1140. <http://dx.doi.org/10.1002/smj.276>.
- Wurzer, T. and Reiner, G., 2018. Evaluating the impact of modular product design on flexibility performance and cost performance with delivery performance as a moderator. *International Journal of Operations & Production Management, [e-journal]* 38(10), pp. 1987–2008. <http://dx.doi.org/10.1108/IJOPM-03-2017-0152>.

- Xue-feng, L. and Yan-xia, W., 2013. Strategic transformation of Shanzhai firms: Evidence from the Chinese case. In: . 2013. 2013 International Conference on Management Science and Engineering 20th Annual Conference Proceedings: IEEE, pp. 789–797.
- Ye, Y., Huo, B., Zhang, M., Wang, B. and Zhao, X., 2018. The impact of modular designs on new product development outcomes: the moderating effect of supply chain involvement. *Supply Chain Management: An International Journal*, [e-journal] 23(5), pp. 444–458. <http://dx.doi.org/10.1108/SCM-01-2018-0021>.
- Zhang, M., Guo, H., Huo, B., Zhao, X. and Huang, J., 2019. Linking supply chain quality integration with mass customization and product modularity. *International Journal of Production Economics*, [e-journal] 207, pp. 227–235. <http://dx.doi.org/10.1016/j.ijpe.2017.01.011>.
- Zhang, M., Zhao, X. and Qi, Y., 2014. The effects of organizational flatness, coordination, and product modularity on mass customization capability. *International Journal of Production Economics*, [e-journal] 158, pp. 145–155. <http://dx.doi.org/10.1016/j.ijpe.2014.07.032>.
- Zhou, S., Gu, Z. and Yuan, J., 2014. Product modularity and supply chain collaboration: An empirical study of firm performance for 221 Chinese manufacturing industries. In: . 2014. 2014 IEEE International Conference on Management of Innovation and Technology: IEEE, pp. 41–47.
- Zirpoli, F. and Camuffo, A., 2009. Product architecture, inter-firm vertical coordination and knowledge partitioning in the auto industry. *European Management Review*, [e-journal] 6(4), pp. 250–264. <http://dx.doi.org/10.1057/emr.2009.25><http://dx.doi.org/10.1057/emr.2009.25>.