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Abstract A lot has been written about the performance effects associated with implementing a higher degree of product modularity in a firm's product portfolio. However, these findings are mostly based on case research in the electronics and automotive industries and have hardly been tested and generalized beyond these industries. To be able to establish whether firms not part of these industries would experience the same performance effects, survey research will be needed. To support future survey research, this paper proposes an operationalization of product modularity and details the link between product modularity and firm performance, to support the future development of measures and hypotheses.

Keywords: Product modularity · Firm performance · Literature study

1 Introduction

The concept of modularity is not new. In fact, its origins can be traced back as far as to 1965, where Martin K. Starr noted that consumers were demanding ever-greater variety, a demand that could be met by modular production, that is, "developing capacity to design and manufacture parts, which can be combined in a maximum number of ways" [1, p. 132]. Plenty authors have further examined and developed the concept during the subsequent years.

Nowadays, most authors agree on the general principles behind modularity. In general, modularity is regarded as a design strategy for building and organizing complex systems effectively [2]. It is viewed as a relative property and depends on the degree to which the interfaces, interactions, or design rules of the system are

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standardized and the degree to which each product component has a clear, unique, and definite function within the system [3–5]. A system is modular if it has standardized interfaces and the components perform one or very few functions. In effect, the coupling and dependency between components are minimal, and the components can be mixed, matched, and changed without compromising the overall functionality and integrity of the system [3, 4, 6, 7].

The problem in the modularity literature is, however, that although many performance benefits have been proposed, these have hardly been tested empirically. One explanation for this lack of empirical verification has its roots in the concept itself. Even though authors agree on the general principles behind modularity, the concept of modularity is ambiguously understood on a more detailed level [8, 9]. Even within the boundaries of the management literature, the concept is measured and operationalized in different ways [10]. There is also a tendency in the literature to generalize findings based upon a limited empirical background [11]. The literature is riddled with examples of companies that have gained from using modular systems. However, most of the case studies derive from the automotive and electronics industries [12]. In addition, the few articles that have examined the performance effects of product modularity quantitatively have operationalized it differently (e.g., [12–19]).

Thus, in order to develop firmer theory, we need large-scale, i.e., survey based, research to (1) test the performance effects reported in the literature but largely based on case studies and (2) generalize these effects beyond the automotive and electronics industries. In order to prepare for such a study, this paper operationalizes product modularity and develops hypotheses on the performance effects of product modularity. This paper focuses on internal firm performance effects, which means that any possible effect that goes beyond firm boundaries, i.e., effects on supplier relations, customer involvement and preferences, or competitor imitation capabilities, is not included. The paper also primarily focuses on *product* modularity, not on service, knowledge, or production modularity, and on *operational* performance, not strategic or financial performance.

2 Research Design

In order to find the articles from which the many proposed performance effects of product modularity originates, a two-step literature study was conducted.

First, a subject search was conducted with the purpose to find articles that examined product modularity and its influence on firm performance. The search was conducted in four databases, confined to English language academic journals, limited to peer-reviewed articles, and reviews published during the last 20 years, and excluded obviously irrelevant areas such as chemistry, medicine, and physics. Based on the above search limitations and the search terms shown in Table 1, 649 articles were found.

Table 1 Search terms used in the literature search

Key words		Key words/title/abstract		Key words
Modular* OR	AND	Typology OR	NOT	Robot OR
Product platform OR		Classification OR		Software* OR
Product architecture OR		Operationalization OR		Programming OR
Product family		Performance OR		Coding OR
		Benefit OR		Psychology OR
		Benefits OR		Bio*
		Effect OR		
		Effects		

Table 2 Measures used in survey research in the modularity field

Measures	Definition
Decomposability and assemblability	The ease to which the product can be decomposed and assembled
Independence	The ability to make changes to key components without changing others
Commonality and carry-over	The ability to reuse components between products and across product generations
Combinability and add-on	The ability to combine and add-on components to create different end products
Other	Standardization of components and processes, use of modular design and use of a standard base unit or technology

This number was reduced to 25 articles by only including articles focusing on *product* and *firm* level and excluding articles that focused on models, metrics, and methods for assessing and achieving modularity, on modularity's performance effects in a very specific context or regarded modularity as one of many ways of achieving certain effects. All of these 25 articles had some preconceptions of how product modularity influences firm performance, either based on logic or on previous articles.

The purpose of the second step was to extend the number of articles and include those that were most influential in forming the preconceptions behind modularity. To do so, the 25 articles' references were turned to. From these references, the 21 articles, books, and paper cited five times or more were added to the literature base.

3 Linking Product Modularity and Firm Performance

Only a handful of articles have attempted to operationalize modularity. These articles, shown in Table 3, are based on survey research. Although they examine different industries and settings—from the first-tier suppliers to the "big three" auto manufacturers in North America [18, 19] to the plastics, electronics, and toy

Table 3 Performance effects reported based on survey research

Article	Findings	Product modularity measures
[13]	Product modularity positively impacts delivery, flexibility, or customer service, but is not correlated with low price and product quality	Decomposability Independence
	Delivery and flexibility are significantly correlated with product performance, but is not correlated product quality, low price and customer service	Commonality Carry-over
[14]	Product modularity positively impacts product innovativeness, flexibility, and customer service, but is not correlated with low price, product quality, or delivery	Standardization of components
	Internal integration and product modularity will interact to significantly improve product innovativeness and has a marginal effect on product quality	
[15]	Product modularity positively impacts NPD time performance, which is moderated through internal integration	Modular design and assemblablility
	Findings do not support the existence of a significant moderating effect of supplier involvement	Commonality
[16]	Product modularity positively impacts NPD time performance and product performance, which is moderated through internal integration	
[17]	Plants with product modularity exhibited significant higher levels of supplier integration and component inventory and higher use of captive retail outlets	Combinability Add-on
	Customer involvement in the assembly and use stages (not in the fabrication stage) and product modularity is significantly correlated with the use of make-to-stock production planning	Commonality Standard base unit or technology
[18]	Product modularity positively impacts manufacturing agility, firm growth, and use of process modularity	
	Process modularity has no impact on manufacturing agility, and manufacturing agility had no impact on growth performance	
[19]	Product modularity has a significant effect on every integration strategy	Modular design and combinability
	Product modularity positively impacts costs, quality, flexibility, and cycle time	Standardization of processes and components
	Product modularity and design/supplier integration will interact to significantly improve flexibility and has a marginal effect on costs	
	Product modularity and manufacturing integration will interact to significantly improve flexibility and has a marginal effect on costs and cycle time	

(continued)

Table 3 (continued)

Article	Findings	Product modularity measures
[12]	Product modularity positively impacts financial performance	Decomposability Independence
	Product modularity positively impacts product variety, but is not correlated with new model and product introduction	Commonality
	Modular structures and processes have direct effects on financial performance, independently of product modularity	Carry-over

industries in Hong Kong [13, 14]—the articles present some comparable findings. First of all, it is found that product modularity positively impacts one or more traditional performance parameters, such as flexibility, customer service, product performance, product innovativeness, and new product development speed, and may or may not influence costs, new product and model introduction, delivery, and quality. Secondly, it is established that the relationship between product modularity and performance is mediated by internal integration.

However, problem is that the findings are based on different measures of product modularity. As illustrated in Table 3, the different authors that have conducted survey research have used different measures to operationalize product modularity. These measures are defined in Table 2.

Furthermore, the above measures ignore some critical aspects of product modularity. Ulrich [4], one of the most referred to articles, defines a modular architecture as having a one-to-one mapping from functional elements to physical components and decoupled interfaces between components. However, both the allocation of functions to the modules and the interfaces has been neglected in the measures.

Yet another problem is that the articles operationalize product modularity by focusing, mostly, on its effects, rather than its characteristics. The extent to which components can be reused, added-on, or carried over are product *effects* of implementing modularity in the product portfolio, while standardization of modules and interfaces, and one-to-one (or few) links between modules and functions are actual *characteristics* of modularity.

Lastly, these findings are based on different and very aggregate perceptions of what performance exactly constitutes. In fact, the relationship between product modularity and firm performance is rather complicated. The complexity of this relationship may partly explain why researchers struggle with determining the exact nature of the connection between product modularity and, for instance, innovation, quality, and costs [20, 21]. This means that there is a need for combining and clarifying what literature proposes the relationships between product modularity and firm performance to be, in order to develop hypotheses to support future research. This article will try to do so, by distinguishing between (1) the *organizational* effects that are expected to derive from and/or enhance the

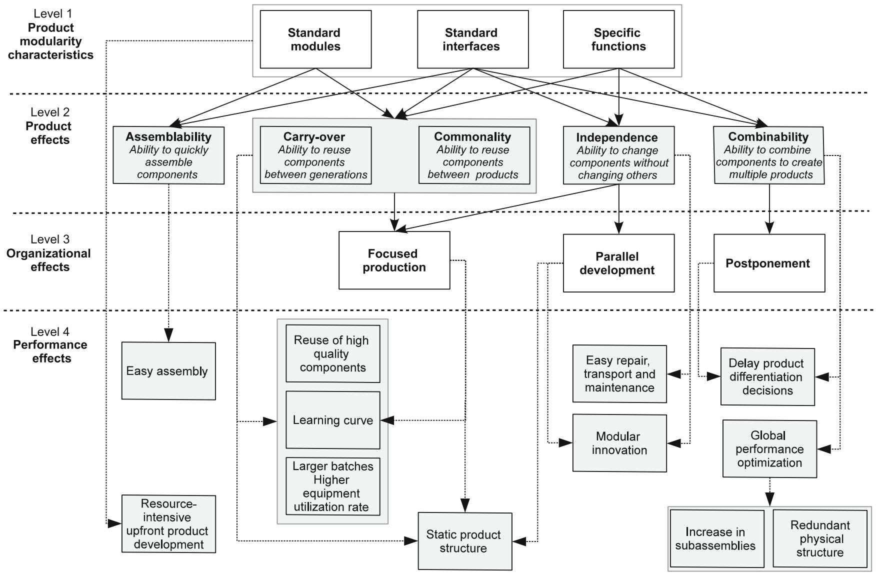

Fig. 1 The link between product modularity and firm performance

proposed performance effects and (2) *performance* effects to be expected from implementing product modularity and these organizational practices.

The remainder of the article is structured according to the model shown in Fig. 1. This model delineates between product modularity *characteristics* and product *effects* and also distinguishes between *organizational* effects and *performance* effects that possibly could be expected to appear after implementing product modularity.

3.1 Product Modularity Characteristics and Effects

This article proposes that product modularity is a function of three product characteristics: the standardization of component interfaces and the component itself and how functions are allocated to the components. This means that the extent to which a firm's product portfolio is modular depends on whether the physical components and connections are standardized and the internal integrity in the product. Standard interfaces refer to the use of physical connections that are well defined and not allowed to change during a period of time [3, 23]. Standard components are components that are designed for the use in several products [4]. Internal integrity refers to consistency between function and structure [24], i.e., the extent to which each component performs one of few functions. If key product functions are dependent on multiple components, it gravely complicates the task of standardizing components or subsystems and their usability in multiple applications [4].

The use of standard interfaces and modules provides the company with several possibilities, which it may or may not utilize. First of all, it allows the existing and future product portfolio to use the same component in several products for the same functional purpose, i.e., it allows for carry-over and commonality. It also facilitates assemblability, as it minimizes the complexity of assembly as the number of components is minimized, and interfaces are well known.

The use of standard interfaces and specific functions enables product changes to one functional element to be localized within one component, which is denoted independence in Fig. 1 [4]. It should also allow the product to be decomposable, i.e., that the product cannot only be quickly assembled, but also quickly decomposed into separate units again, which facilitates a "plug-in and plug-out flexibility." The combination of standard interfaces and specific functions also helps attaining combinatorial assembly from relatively few components, that is, combinability [4], allowing the "mixing and matching" of components to give a potentially large number of product variations [25].

3.2 Organizational Effects

The combinability of components allows for form [26] or manufacturing postponement [27]. Postponement is based on the principle of seeking to design common platforms, components, or modules, and delaying final assembly or customization until the final market destination and/or customer requirements are known [28]. It implies that the customer order decoupling point, the point that divides the order-driven, and the forecast-driven activities, is pushed upstream [26], in the form of, for instance, assemble-to-order.

Product modularity not only allows for the decoupling of components, but also the decoupling of tasks [29]. This enables product development, after the system-level design phase, to be conducted by relatively independent teams [7]. Different parts of the design can be worked on independently and parallel to each other [5]. In other words, when a firm creates modular designs with well-defined interfaces, the need for component developers to interact is greatly reduced, which enables a firm to adopt a "modular" organization design for product creation processes [3]. Similar effects can be expected in production, where modular designs allow a firm to divide its production into specialized groups with narrow focus areas [4].

3.3 Performance Effects

One of the most mentioned benefits of product modularity is the possibility to achieve economies of scale on component level [30]. Reusability allows the components to be produced in higher volumes using larger batch sizes [29]. This means that change over times and costs are reduced and a higher equipment utilization rate can be expected. In addition, development resources and capital expenses can be amortized across a larger range of units [29], lower spare parts, and safety stock levels are needed and, if the component is outsourced, larger batches can be purchased at increasing discount rates. The performance effects that can be expected from achieving component economies of scale include lower unit manufacturing costs, shorter manufacturing lead-time, and higher-throughput time efficiency.

Related to economies of scale is the notion of the learning curve. Reusing components means that the total number of *different* components to be manufactured decreases and the workforce will attain a comparatively higher degree of experience with producing the specific components, especially if they are reused in different product generations. As these components, carried over from previous generations, have already been tested extensively in practice, product modularity may increase durability and reliability. Additionally, if the components that are carried over are of proven high quality, a firm can expect lower scrap and rework costs and higher conformance and product quality.

Another performance effect of product modularity highlighted in the literature is related to postponement [4, 18]. A greater variety of products can be constructed from a smaller set of components [29], tailored according to customer order, and assembled or configured to order. The bulk of the components, rather than final products, can be stocked [29], resulting in shorter-order lead-times and improved responsiveness for customized products, and also decreased inventory costs, as fewer variants need to be, kept in stock [31].

The assemblability and decomposability of the product facilitated by product modularity, enables easier, and therefore, less costly and faster assembly. The ability to decompose the product also supports repair and maintenance, as any dysfunctional element can easily be removed and replaced, reducing rework cost [29].

The relationship between product modularity and innovation is more ambiguous than the above relationships and much discussed in the literature. On the one hand, product modularity, especially the independence of components and parallel development, facilitates incremental and modular innovation. Concurrent development of components may increase the efficiency of product development and time to market [5, 23]. Additionally, modular upgradable products enable economies of substitution, where technological progress may be achieved by substituting certain components while retaining the others [6]. The components that are retained in the product structure can, subsequently, undergo a series of incremental improvements.

Through developing new and improved components based on new technologies that fit into the overall product architecture and by giving component developers the opportunity to experiment with new component designs, the innovativeness and introduction speed of new technologies can be accelerated [2, 23]. This enables the firm to offer greater product variety and customize products to suit many different customer segments [32].

However, it is important to note that, although modular innovation may enhance performance at the module level, it does not necessarily do so on system level [33]. Excessive modularization may result in enhanced system complexity from the perspective of the designer, where the designer may become blind to possible important interactions between component improvements and system-level performance [33].

Even though modularity may facilitate rapid innovation, firms will also experience resource-intensive upfront development before being able to make use of these benefits, as the initial design efforts needed to create a modularized product portfolio are much higher than designing comparable integrated systems [2], and may include design changes in the manufacturing system, too [32]. It requires extensive architectural knowledge to be able to define which components and interfaces need to be standard and establish how functions can be allocated to components.

Finally, a modular product portfolio does not imply sustainable advantages. From time to time, not only the components, but also the entire product structure may require an update. Innovation at this level, also called architectural innovation, can be difficult for firms geared toward innovation on a modular level, as these firms over time will have developed organizational structures and information channels that are focused on component-level activities [25]. So, architectural innovation creates problems for the established firm, as it alters the way in which the components of a product are linked together [34].

Another side effect of increasing product modularization is that components are not optimized for one application but have been designed so that they meet the requirements of multiple products. This is called global performance optimization in Fig. 1, and means that, compared to integral products, the individual products that are part of a modular product portfolio may have lower levels of performance or that components have excess capability when used in some particular applications [29]. An integral product allows for function sharing, i.e., implementing multiple functions using a single element, which allows for redundancy to be eliminated and geometric nesting minimizing the mass, size and material use of a product [7]. Modular product portfolios, on the other hand, may have redundancy in the physical structure, increasing size and mass, material use and in the end, variable costs. The fact that there is less function sharing in modular products may also increase the number of subassembly steps needed in production.

Finally, modularity has also been highlighted as a tool to achieve mass customization and is seen as a part of platform thinking. Pine [30] even states that creating modular components is the best method of achieving mass customization—minimizing costs, while maximizing individual customization. Meyer and Lehnerd [35] argue that companies should plan and manage on the basis of product platforms, the combination of subsystems and interfaces that constitute a common product structure for a series of derivative products. The clearly identified interfaces between subsystems of the product would then provide the product designers with the degree of freedom needed for rapid and cost-efficient creation of derivative products [35].

4 Summary and Further Research

4.1 Summary

There is little robust theory on the practical effects of implementing a higher degree of product modularity in a company's product portfolio. In order to test this, mostly case research based, findings reported in the literature and establish whether the many benefits suggested extend beyond the automotive and electronics industries, large-scale survey research is needed. To support such research, this paper proposes an operationalization of product modularity and details the link between product modularity and product, organizational, and performance effects, to support the future development of measures and hypotheses.

Operationalization of product modularity and its effects By taking outset in the measures used in survey research as well as the most widely recognized definitions, this paper proposes that product modularity should be operationalized by including (1) its characteristics—the degree of standardization of interfaces and components and the degree of internal integrity within the product portfolio—and (2) its product, organizational, and performance effects. *Product effects* include the degree to which the firm can carry-over or reuse its components between products and product generations, and the independence, combinability, and assemblability of components. *Organizational effects* include (1) moving the customer order decoupling point upstream by implementing assemble-to-order or even configure-to-order production, (2) decoupling of activities in product development, as well as (3) focused, i.e., specialization of, production activities. The extent to which these effects are implemented affects the extent to which *performance effects* are achieved, in terms of, for example, shorter-order lead-times, improved responsiveness, decreased inventory costs, and increased speed, and reduced cost of new product development.

The role of time It takes time and money to implement and make the best use of modularity. Creating modularity requires a large amount of upfront development costs as well as resources. Modularity facilitates incremental and modular innovation. However, over time, architectural innovation could be needed, which may be difficult to cope with for a company whose performance is based on an established architecture. Finally, the learning curve effect is fostered by the reuse of standards, both in terms of modules and interfaces, which, in the long run, improves speed, quality, reliability, and, thereby, reduces costs.

4.2 Further Research

Figure 1 together with the operationalizations proposed in this article will provide the basis for the development of a survey questionnaire. In preparing that instrument, the role of context needs to be addressed as well, considering that, for example, product modularity may prove to be overkill in very stable markets and in markets where there is no need for high product variety. In environments with very volatile changes in, for example, product technology, or demanding very levels of high customization, modularity may not be the appropriate solution, either. As Ernst [11] highlights, a feature of modular systems is their rigidity, as interface standards are difficult to adjust. Any transition to a new generation of design architecture requires fundamental changes in system components, and if these transitions are required too often, product modularity may not be the correct solution [11].

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