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Operationalisation and Measurement

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Published in:
14th International CINET Conference

Publication date:
2013

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Boer, H. E. E., & Hansen, P. H. K. (2013). Product modularity and its effects on firm performance: Operationalisation and Measurement . In *14th International CINET Conference : Business Development and Co-creation* (14 ed., pp. 174-184). Continuous Innovation Network. http://www.continuous-innovation.net/

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PRODUCT MODULARITY AND ITS EFFECTS ON FIRM PERFORMANCE: OPERATIONALISATION AND MEASUREMENT

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ABSTRACT

The literature promises a large range of benefits to firms that adopt product modularity. However, the term product modularity is ambiguously understood and its benefits have not been empirically validated through large-scale studies. By reviewing existing literature, this paper seeks to operationalise product modularity and firm performance, to support further and more detailed empirical studies of product modularity's performance effects. The review shows that, so far, the operationalisation of product modularity has been incomplete, and suggests that modularity needs to be operationalised by assessing the level of 1) standardisation of a product portfolio's modules (including functional specificity) and 2) standardisation of module interfaces (including decomposability). Furthermore, in order for the research community to move forward, performance effects need to be examined on a more operational level, by looking at performance indicators for both the product development and production processes in the firm.

Keywords: Product Modularity, Firm Performance and Literature Review

1. INTRODUCTION

Product modularity makes intuitive sense. Decomposing a firm's product portfolio into smaller, manageable portions that are easily mixed-and-matched seems easy enough. Moreover, the literature promises a wide range of benefits associated with modularity. However, the problem is that both practitioners and scholars have struggled with the concept of modularity, its implementation, and actually demonstrating the benefits. Thus, the question remaining open is: *What performance effects can be expected from the implementation of (a higher degree of) modularity in a firm's product portfolio?*

2. THEORETICAL BACKGROUND

Product modularisation is to a large degree a method of complexity reduction, as it is a way of organising complex products into simpler modules that can be managed independently and used interchangeably in different configurations without compromising system integrity (Baldwin & Clark, 1997; Sanchez & Mahoney, 1996). This independence allows for design changes to be made to one module without requiring a change to other modules for the product to function properly (Gershenson *et al*., 2003; Sanchez & Mahoney, 1996). There is an increasing interest in the modularity concept (Gershenson *et al*., 2003), which is no wonder given the wide range of benefits proposed in the literature and in view of the suggestion that modular designs improve competitive capabilities (Baldwin & Clark, 1997; Lau Antonio *et al*., 2007).

In spite of the increasing interest, the modularity literature still faces two critical issues: 1) *limited empirical evidence* and 2) *varying definitions of the key concepts*. Most research reported in the modularity literature is based on the success stories of

individual firms (Pasche *et al*., 2011), typically from the automotive and electronics industries, and presented in the form of post-hoc, prescriptive examples (Campagnolo & Camuffo, 2010; Ernst, 2005; Genba *et al*., 2007; Worren *et al*., 2002) The question is whether these findings can be generalised to other industries, industries that not have achieved any mature level of modularity. Furthermore, the concept of modularity is multi-faceted and still in a fluid and transitional state (Jacobs et al., 2007; Watanabe & Ane, 2004), where there is a lack of comparison among the varying definitions of modularity (Gershenson *et al*., 2003). This has led to a wide spectrum of methods used to measure and assess modularity and its effects, upon which different methods of implementing modularity are based (Gershenson *et al*., 2003; Hansen & Sun, 2011).

In addition to these general issues, there are several subtopics within the literature, which require further attention:

- *Modularity and innovation:* Does modularity foster the "*modularity trap*" (Chesbrough & Kusunoki, 2001), wherein organisations adapted to modular products become incapable of capturing value from their innovation capabilities when the technology becomes more integral. Or does it solve the "*complexity catastrophe*" (Baldwin & Clark, 2000), where organisations producing integrated products only can implement small, isolated changes due to an increasing number of tasks needed to resolve the dependencies within the product? Can companies adopt modularity and its innovation benefits and still deter imitation (Ethiray, 2007; Pil & Cohen, 2008)?
- *Modularity and configuration*: Is there a convergence between product, knowledge, organisation, and/or supply chain modularity? Does modularity call for loose supply chain relationships (Fine, 2000) or does it require strong collaboration to deliver modular products (Brusoni & Prencipe, 2001)?
- *Modularity and maturity*: Architectural knowledge, that is, knowledge about the system components and their interactions, can "*emerge only after an organisation has developed sufficient experience with a problem to be able to fragment it into elements without losing critical information"* (Henderson, 1992) and when production processes have emerged to a point where explicit design rules can be developed (Abernathy & Utterback, 1978). But, what is sufficient experience and what are mature production processes? And, arguably even more important is the question, what organisational characteristics and resources are needed for a firm to be able to use product modularity effectively?
- *Modularity and firm performance*: The literature promises a great number of benefits associated with modularisation, but no large-scale studies have been reported that validate this association (Gershenson *et al*., 2003; Lau Antonio *et al*., 2007).

Even though all of these issues are worth examining, the last topic is especially important. In the early phases of product development, most of the total product life-cycle costs are determined. Although firms are becoming better in including production aspects early on (for instance through concurrent engineering), there is still a lack of an entire lifecycle perspective (Campagnolo & Camuffo, 2010) on the prerequisites for, and the effects of, modularisation. There are plenty of authors arguing for the life-cycle benefits of modularisation (e.g. Hsuan & Hansen, 2007; Hansen & Sun, 2011) or even going so far as to claim that modularity can help firms to move beyond the variety-volume trade-off (Wheelwright & Hayes, 1985), capture both economies of scale and product variety, and introduce technologically improved products more rapidly (Gershenson *et al*., 2003). However, firms will need more than vague qualitative

arguments in order to for them to decide to adopt modularisation or continue their modularisation efforts.

3. RESEARCH OBJECTIVE

To recall, there are two general weaknesses in the modularity literature, limited empirical evidence and ambiguous definitions of core concepts, while one of the challenges concerns the relationship between modularisation and firm performance. Thus, in order to be able to tackle this challenge and support a study on the performance effects of modularity in a wider range of contexts, the objective of this paper is to operationalise "*product modularity*" and "*firm performance*".

4. METHODOLOGY

In order to operationalise modularity and performance, point of departure is taken in existing literature that has examined modularity and its influence on performance. The reason for this is straightforward. It was assumed that, in order to be able to write about modularity and firm performance, and discuss or perhaps even empirically show advantages associated with modularity, authors must have operationalised or at least have had some pre-understanding of modularity.

To find such papers, a subject search was conducted using four databases. The search was conducted within English language academic journals and was limited to peer reviewed articles and reviews published during the last 20 years. The search terms, shown in Table 1, were based on the constructs "modularity", "performance" and "operationalisation".

Key Words		Key Words/Title/Abstract		Key Words
Modular OR* *Product platform OR* *Product architecture OR* *Product family*	AND	*Typology OR* *Classification OR* *Operationalisation OR* *Performance OR* *Benefit OR* *Benefits OR* *Effect OR* *Effects*	NOT	*Robot OR* *Software* OR* *Programming OR* *Coding OR* *Psychology OR* *Bio**

Figure 1 – Search Terms used in the Literature Search

Modularity is in itself a broad term used in many different scientific fields. Therefore, in addition to ensuring that certain topics were excluded in the search string, specific areas where excluded, such as for instance chemistry, medicine, and physics.

Description	# Articles
Modularity and specific performance effects for a focal firm or modularity's performance effects in specific company processes	25
Models, metrics and methods for assessing and achieving modularity	78
Modularity's performance effects in a very specific context or seen as one of many ways of achieving certain effects	29
Product modularity and performance, not on firm level, but rather on supply chain, industry, or supplier level	37
Other	17

Table 2 – Categorisation of Articles found in the Literature Search

After sieving through the titles and abstracts of the resulting 649 articles, yet another round of articles were removed, this time based on the fact that they did not focus on either product modularity, but rather on production, service, assembly modularity or the like, or on businesses, but rather on, for instance, computer systems, hydrology or biology. The remaining 187 articles were categorised in five different groups, illustrated in Table 2. A total of 25 papers were found that directly address product modularity and firm performance. These articles constitute the core of the article.

5. OPERATIONALISATION OF PRODUCT MODULARITY

Most authors agree on the contours of product modularity. In general, modularity is a strategy to organise complex products and processes efficiently and effectively (Baldwin & Clark, 1997). Modular products are often contrasted against integral products, products that have a complex mapping from functional elements to physical components and/or have coupled interfaces between components (Meyer & Lehnerd, 1997; Ulrich, 1995). Modular products, in contrast, have decoupled interfaces and similarity between the physical and functional architectures, i.e. each module has a clear and distinctive function (Eom, 2008; Ulrich, 1995; Danese & Filippini, 2010; Ulrich & Tung, 1991).

However, products are rarely strictly modular (or integral). Most products are just more (or less) modular than comparable products (Meyer & Lehnerd, 1997). In other words, modularity is a relative property. Furthermore, products can be decomposed at different levels (subsystems, components, subcomponents) so that modularity can be a characteristic of each or only some of these levels (Brusoni & Prencipe, 2001, p. 183).

The above statements describe modularity in very general terms. The next subsections dig beneath the surface and present how the concept has been operationalised in articles examining the effects of product modularity on firm performance.

5.1 MEASURES USED TO OPERATIONALISE PRODUCT MODULARITY

Only a handful of articles have attempted to measure modularity using multiple variables – see Table 3. The general gist of these articles is that measuring modularity involves assessing:

- Whether modules are standardised and common, so that they can be re-used in multiple products, carried over to next generations, or added on products.
- Whether products are designed to have interchangeable features, i.e. changes can be made to key modules without redesigning others.
- The ease and speed of assembly and disassembly of the product.

In order to explore the effects of modularity and customer involvement on materials management practices in plants producing mass customised products, Duray (2004) adds two other features to the operationalisation of modularity, by dividing modularity into fabrication modularity and standard modularity. Standard modularity, where modules are arranged and combined to customer specification, resembles what other authors have called product modularity. In addition to assessing whether components are common and have interchangeable features, it is assessed whether the features are designed around a base unit or around a common technology, in order to apprehend the degree to which a company has implemented standard modularity. The other form of modularity, fabrication modularity, denotes a company's capability to design new or alter existing components to meet customer specifications. This resembles a company's product customisation capability.

Authors	Variables used to assess modularity
Lau Antonio *et al*. 2009 Lau Antonio *et al*. 2007	**Product modularity** • *Product can be decomposed into separate units* • *We can make changes in key components without redesigning others* • *Product components can be reused in various products* • *Product has a high degree of component carry over* • *Product's components are standardised*
Danese & Filippini 2010 Danese & Filippini 2013	**Product modularity** • *Our products are modularly designed, so they can be rapidly built by assembling modules* • *Our products are designed to use many common modules* • *We do not use common assemblies and components in many of our products (reverse scored)*
Duray 2004	**Fabrication modularity** • *Components are designed to end-user specifications* • *Components are sized for each application* • *Components are altered to end-user specifications* • *Component dimensions are changed for each end-user* **Standard modularity** • *Products have interchangeable features and options,* • *Options can be added to standard products,* • *Components are shared across products,* • *Features designed around standard base units* • *Products designed around a common core technology*
Jacobs *et al*. 2007 Jacobs *et al*. 2011	**Product modularity** • *Modularity: The process of developing interchangeable parts across products that can be reconfigured into a wide variety of end products* • *Standardisation: The use of standard procedures, materials, parts, and or processes for designing and manufacturing a product*
Pasche *et al*. 2011	**Platform characteristics** **Degree of implementation** • *Products based on platforms (share)* • *Sales – products based on platforms* • *Number of different platforms* • *Number of common components* • *Value of common components* **Degree of experience** • *Number of different platforms* • *Year – start – platforms* • *Year – products (sales) from platforms* • *Platforms – life cycle (years)*
Worren *et al*. 2002	**Modular products** • *Our products have been decomposed into separate modules* • *For our main product(s), we can make changes in key components without redesigning other* • *The extent of reuse of components* • *The degree of component carry-over*

Table 3 – Measures used to Operationalise Product Modularity

Jacobs *et al*. (2007; 2011) add that, in addition to examining whether components are standardised, modularity also requires standardisation of design and manufacturing procedures and processes. Pasche *et al*. (2011) do not directly assess product modularity, but are more interested in investigating the effects of platforms on new product

development by looking at the company's degree of implementation and degree of experience with modularity.

In order to establish if these measures are representative of the characteristics of modularity as proposed in the research community, the next subsection will look at these characteristics.

5.2 Characteristics of Modularity

Table 4 summarises the attributes often used in the literature to define modularity.

One problem is that some of the attributes are directly addressed in the measures presented above; others are not, in particular, the interfaces and relationships between modules, the allocation of functions to modules, the relationships within modules, as well as the structure of modules.

One of the problems with defining modularity is that there is lack of consensus with regards to what interfaces actually are. Some authors agree that interfaces are the connections between subsystems (e.g. Meyer & Lehnerd, 1997; Mikkola, 2006) whereas others (e.g. Baldwin & Clark, 2000) view interfaces as design rules and visible information, which constitute a pre-established way to resolve potential conflicts between interacting parts of the design. These design rules denote how designers should handle the interactions between components, by making a parameter choice into a pre-determined decision. However, both types of interfaces need to be well defined and standardised. The interfaces also need to be loosely coupled, that is, there needs to be a relative independency between distinct components (Orton & Weick, 1990). This notion is closely related to the relationships between modules in modular products. Here, the goal is to minimise the dependency between modules and the processes they go through, and only let the dependencies remain that are fundamental to the primary functions of the product. Structural units that do exhibit a high dependency and similarity in physical properties, processes or functional impact need to be confined within modules, in such a manner so that module boundaries can easily be defined (Gershenson *et al.*, 2003). These modules need to be designed in such a manner, that they can be used in a large range of products and be substituted easily.

One of the most frequently used definitions in the modularity literature is presented by Ulrich (1995), who states that in addition to decoupled interfaces, there should be a one-to-one mapping from the functional elements in the function structure to the physical components of the product. This means that the function of each module needs to be clear and distinctive.

One of the characteristics of modular products can be traced back to Simon (1962) in his article about the architecture of complexity, where he finds that many complex systems have a nearly decomposable, hierarchical structure. For a product to be modular, it should be a decomposable, hierarchically nested system, instead of having interconnected or sequential structures (Baldwin & Clark, 2000).

Attribute	Characteristics*
Interfaces between modules	*Loosely coupled* *Well-defined* *Standardised* *"Frozen" for a predetermined period of time*
Relationship between modules	*Attribute independency - minimal reciprocal interdependencies, minimal incidental interactions, and/or weak connections between components* *Process independency - independent parameters, tasks, design, improvement, manufacturing, assembly, testing or even lifecycles* *Generally fundamental to the primary function of the product*
Module characteristics	*Self-contained - Module boundaries are easily identified* *Standard* *Can be removed, recombined, transferred, replaced and/or are psychically detached non-destructively, with little loss of functionality and/or without compromising system integrity and performance.* *Can be integrated into different systems for the same functional purpose with only minor modifications* *Structural units of a module are powerfully connected* *Components of a module exhibit similarity in processes, psychically and/or in functional purpose and impact*
Allocations of functions	*Similarity between psychical and functional architectures* *Specificity: Functions are clear, unique, definite and/or distinctive*
Product characteristics	*(Near)-decomposability - the products can be easily disassembled, decomposed and/or disaggregated* *Hierarchical - products are have a hierarchical pattern and/or are hierarchically nested system*
Heterogeneous outputs	*Modules are used in a large range of products* *A large range of modules can be substituted*

Table 4 – Attributes used to Describe Product Modularity

* Sources: Arnheiter & Harren, 2006; Baldwin & Clark 1997; Baldwin & Clark, 2000; Ethiray *et al*., 2008; Brusoni & Prencipe, 2001; Garud & Kumaraswamy, 1993, 1995; Gershenson *et al*., 2003; Jacobs *et al*., 2011; Meyer & Lehnerd, 1997; Sanchez & Mahoney, 1996; Schilling, 2000; Worren *et al*., 2002; Ulrich 1995; Ulrich & Eppinger 2012; Ulrich & Tung, 1991

5.3 DISCUSSION

Operationalising modularity is not easy as it is a relative property, dependent on the architecture of similar products and on the unit of analysis. In addition, the concept is ambiguously understood on a more detailed level. The current measures used in literature also only seem to partially be able to capture modularity as a concept, and focus on product modularity by looking at standardisation of components, interchange-ability and ease of assembly.

The measures all agree on product systems or families as the unit of reference, which makes sense, as modularity only can convey advantages if modules are mixed and matched across products. In order to assess modularity in different firms, the best unit of analysis seems to be at the highest hierarchical level of the product structure, as this can capture any firm whose products consist of multiple components assembled into final products.

One issue with the current measures, however, is that there is a focus on the effects of modularity, rather than modularity itself. For instance, the fact that components can be reused or carried over to other products and that changes can be made to key modules with little loss of functionality are effects of implementing modularity in the product portfolio, rather than measures of modularity. Instead, this article proposes that modularity is dependent on the two product characteristics: module interfaces and the module itself. This view is illustrated in figure 1.

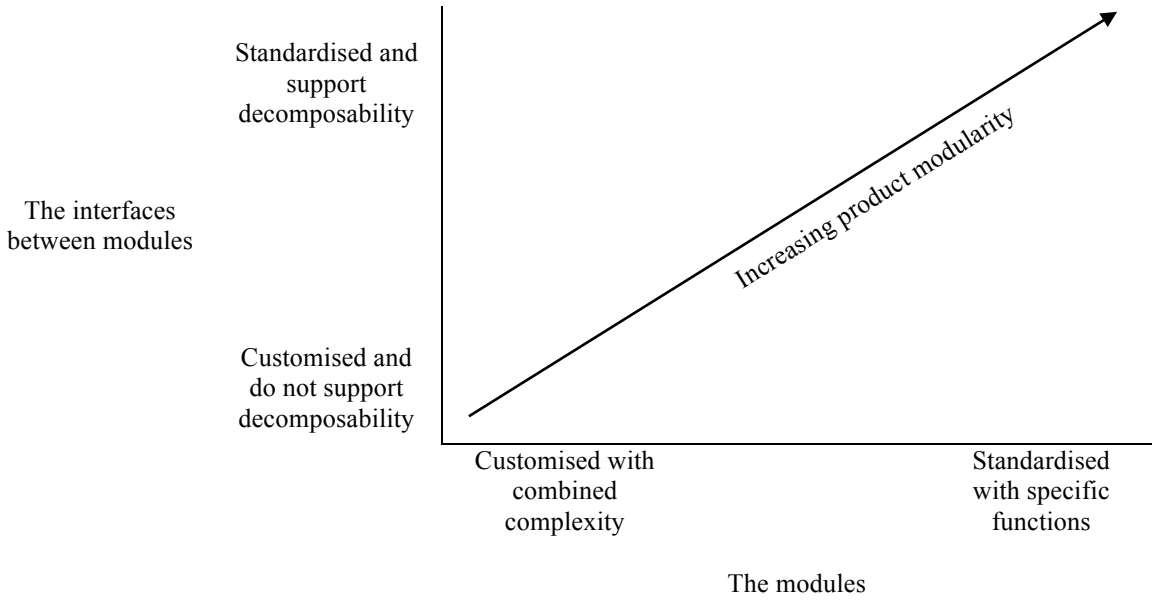

Figure 1 – Continuum Describing the Degree of Modularity

From this perspective, the extent to which a firm's product portfolio is modular depends on whether:

- The psychical connections between components are 1) standardised and 2) ensure that the product is decomposable, i.e. that the time and effort required to assembly or disassembly the product is minimal.
- The components are standardised, which refers to the ease of which modules can be integrated in different systems for the same functional purpose. This implies that each module has a clear and distinctive function.

These characteristics can assist in hypothesising relationships between product modularity and firm performance. First, however, there is a need to establish which performance effects already have been established in the literature.

6. MODULARITY'S EFFECTS ON FIRM PERFORMANCE

The articles included in the literature review have examined modularity's performance effects through surveys, case studies, experiments, modelling, or through logical reasoning. The effects studied are wide ranging, focusing on:

- Traditional performance measures, such as quality, flexibility, costs, delivery, reliability and speed (Arnheiter & Harren, 2006; Bierly III *et al*., 2008; Jacobs *et al*., 2007; Guo & Gershenson, 2007; Lau Antonio *et al*., 2007, 2009; Watanabe & Ane, 2004).
- New product development time (Danese & Filippini 2010, 2013).
- R&D efforts and incentives (Ethiray, 2007; Genba *et al*., 2005).
- Innovation (Ethiray *et al*., 2008; Pil & Cohen, 2006; Worren *et al*., 2002).

- User preferences (Chung *et al*., 2012),
- Manufacturing agility (Jacobs *et al*., 2011).
- Strategic flexibility (Watanabe & Ane, 2004; Pasche & Sköld, 2012).
- Material management practices (Duray, 2004).
- Integration and coordination mechanisms (Jacobs *et al*. 2007, Pasche & Sköld, 2012).
- Project performance, performance measurement and process adaptation (Pasche *et al*., 2011).

In general, product modularity is found to have a positive effect on one or more traditional performance measures, i.e. cost, quality, speed, and/or flexibility. Jacobs *et al.* (2007) even find that product modularity positively influences each of the above performance measures. However, other studies have produced mixed results.

Lau Antonio *et al.* (2007, 2009) find that product modularity positively affects flexibility, measured in terms of the extent to which the company can provide a wider product range, order size flexibility, a greater number of new products and rapid design changes to customers. Jacobs *et al.* (2007) agree, but measure flexibility in terms of volume, mix, changeover and modification flexibility. There seems to be some lack of consensus on how product modularity influences strategic flexibility. Watanabe & Ane (2004) find that product modularity enables the firm to assemble on a single assembly line single models in several variants (operational flexibility), several models, each of which is a variation of a single platform (strategic flexibility), and customized models (structural flexibility). Pasche & Sköld (2012), however, conclude that product modularity can decrease strategic flexibility, as it reduces the company's ability to react to continuously changing standards.

Product modularity has been found to positively influence new product development time (Danese and Filippini, 2010, 2013), manufacturing and delivery speed (Jacobs, 2011; Watanabe and Ane, 2004). In their original study of the plastics, electronics and toys industries in Hong Kong, Lau Antonio *et al.* (2007) find that product modularity is positively related to speed. Later, however, they find no significant correlation between product modularity and speed (Lau Antonio *et al.*, 2009). Note that these authors use the term delivery, but actually measure speed as they focus on the organization's ability to provide faster and dependable deliveries and reduce manufacturing lead-times. Based on an examination of a major global truck manufacturer's four brands, Pasche *et al.* (2011) find that initial product development requires much time and a high initial investment, and that the performance effects, including speed and costs, are likely to occur in later stages of the product life cycle. This may explain why Lau Antonio *et al.* (2007, 2009) find no significant correlation between product modularity, costs, and also quality (Lau Antonio *et al.* 2007; 2009). Arnheiter and Harren (2006) also find the relationship between quality and product modularity to be a tricky one: six of the eight quality dimensions these authors examined are potentially positively affected by modularity, while five of the eight dimensions may be affected negatively.

The relationship between product modularity and innovation is also unclear. On the one hand, modularity is said to facilitate new product development speed and incremental innovation (Bierly III *et al*., 2008; Danese & Filippini, 2013). On the other, it also enhances the risk of imitation and makes radical and/or architectural innovation more difficult (Bierly III *et al*., 2008; Pasche *et al.,* 2011; Pil & Cohen, 2006).

Finally, product modularity is found to affect the allocation of R&D incentives, the use of materials management practices and integration practices, and the firm's strategic flexibility (Duray, 2004; Ethiray, 2007; Pasche & Sköld, 2012; Watanabe & Ane; 2004).

Generally, the effects studied so far have been very aggregated, and in order to be able understand the underlying reasons for the results, existing literature and logical reasoning is often turned to.

Although the proposed advantages and disadvantages of product modularity extend themselves throughout the supply chain, the focus of this article is firm performance. Therefore, only the benefits and disadvantages internal to the operations of the company have been included in the next sections. The modularity literature tends to delineate between two different areas within the organisation: the product development process and the fabrication and assembly processes. Taking an outset in the previously defined characteristics of modularity, that is, the nature of the interfaces and components, the performance of firms with modularised products can be considered on a more operational level, and compared with the performance of firms producing similar products based on integral designs.

6.1 Product Modularity's Effects on Product Development

In terms of product development speed and costs, product modularity can have both negative and positive effects. The use of standard interfaces and components enables the use of parallel development and reuse of existing components, which can enhance product development speed and also minimise costs (Baldwin & Clark, 2000; Ulrich & Eppinger, 2012; Ulrich & Tung, 1991). However, these benefits can be offset by the high upfront development costs associated with product modularity, as the creation of standard interfaces, modules with specific functions and decomposable products can be a long and challenging process (Baldwin and Clark, 2000; Ulrich & Eppinger, 2012).

The same ambiguity exists when considering the output of the product development process. One the one hand, modularity supports modular and incremental innovation (Mikkola & Gassman, 2003; Pil & Cohen, 2006). Changes to one part of a product should not affect other parts of the product, allowing for innovations to be based on changes in one or a few components, rather than changes to the entire product (Baldwin & Clark, 2000; Ulrich & Eppinger, 2012). Furthermore, using the same or similar components over and over again facilitates the incremental improvement of those components – the so-called learning curve effect (Gershenson *et al*., 2003). One the other hand, using standard interfaces and components may imply that the entire product architecture becomes very static, i.e. changes are only made on module level (Ulrich & Tung, 1991). Here, the company can come to face a situation where it experiences great difficulty when it comes to more radical or architectural innovation (Bierly III *et al.,* 2008). Forcing designers to conform to standard interfaces and use existing modules limits their creativity, may lead to overreliance on existing modules, and hinder innovation.

When it comes to flexibility and quality, modularity seems to be a good idea. Product modularity allows making changes, at least on a modular level, relatively late in the product development process. However, firms may not be able to react quickly to continuously changing demands (Pasche & Sköld, 2012). Furthermore, it facilitates trial and error learning, where experiments can be conducted on each design independently. In addition, it facilitates the reuse of high quality components. However, as Arnheiter &

Harren (2006) note, the perceived quality, general system performance and aesthetics may suffer.

6.2 Product Modularity's Effect on Production and Assembly

One of the most mentioned benefits of product modularity is possibility to combine economies of scale with a varied product portfolio (Gershenson *et al.,* 2003; Mikkola, 2006; Ulrich & Tung, 1991). It allows for delaying design, manufacture and product differentiation decisions, producing modules in larger volumes and enhancing equipment utilisation and, thus, not only reducing production costs but also minimising production lead-time. In addition, standardised components lead to reduced carrying costs, as inventory levels, in the form of spare parts, safety stock and end-product stock, can be reduced and risks can be pooled (Danese & Filippini, 2013). However, some authors also mention that product modularity, and especially the aspect of functional specificity, can lead to increased component inventory and variable costs, if modules are over engineered and, in effect, exhibit less function sharing (Duray, 2004; Ulrich & Tung, 1991). An integral product architecture allows for redundancy to be eliminated through function sharing and allows for geometric nesting of components to minimize the volume a product occupies, which also allows material use to be minimised (Ulrich & Eppinger, 2012). Functional specificity can also have another negative effect, as it can increase the time needed to assemble the sub-assemblies, in comparison to integral products, which can be produced in their entirety. Having a high level of decomposability and standardised interfaces can offset this negative effect, allowing for a quick assembly of the product, or even parallel production. In addition, the before-mentioned learning curve effects can also support the continuous improvement of speed and quality in the fabrication of components and the assembly of final products, and, in the long run, lead to cost minimisation (Gershenson *et al*., 2003; Ulrich & Eppinger, 2012).

7. Conclusion and Further Research

The lack of large-scale verification of the performance benefits of product modularity can hinder the implementation and the continued support of product modularisation in firms, even though, in theory, modularisation can help firms overcome the all-important variety-volume trade-off and has benefits throughout the product life cycle. Other authors also have noted this lack of evidence and some research has been done on how product modularity affects performance.

However, there is still work to be done. Most articles have not operationalised product modularity, although it is an ambiguous term with varying definitions. The authors who have done so, have measured product modularity in different manners. In general, they have focused on the standardisation of modules, the interchangeability of modules and the ease and speed of assembly. However, this article takes the position that interchangeability, i.e. the ability to make changes to key components/modules without redesigning others, is an effect of modularity, rather than a characteristic of it.

Furthermore, the measures have omitted two aspects of modularity often used in defining modularity, namely the nature of the interfaces and the allocation of functions to modules. The performance effects measured so far are also very aggregated, except for the research examining NPD time performance, and results are not conclusive. Most authors agree on the fact that product modularity positively influences flexibility and speed, but these effects can be offset by the initial time required to develop the product,

thus minimising strategic flexibility. The relation to quality and costs are less known. Thus, in order for the product modularity field to move forward, these performance effects need to be examined on a more operational level, i.e. product development, fabrication and assembly performance.

7.1 FURTHER RESEARCH

To support an examination of product modularity's effects on firm performance, three key aspects need to be considered: operationalisation of 1) modularity and 2) performance, and 3) sampling.

Modularisation – This paper proposes to measure modularisation using the two product characteristics shown in Figure 1, that is, whether 1) the psychical connections between components are standardised and ensure that the product is decomposable, and 2) whether the components are standardised and have a clear and distinctive function. Some of the measures already used in previous research could be reused, i.e. the measures that refer to the standardisation of modules and ease of decomposability.

Performance – In order to get a more detailed understanding of how product modularity influences firm performance, performance metrics are needed for product development as well as fabrication and assembly. Some performance metrics, that is, speed, innovativeness, and costs, are relatively easily divided between the two processes, whereas quality and flexibility are not. Speed of new product introduction, product innovativeness, and R&D costs are specific to product development, whereas unit manufacturing costs and lead-time, throughput time efficiency and inventory costs are specific to manufacturing and assembly. More generic metrics, such as time-to-market, delivery speed and labour productivity could supplement the research. Quality, however, is not as easily measured on process level, and could instead be measured in terms of scrap and rework costs, customer complaints, manufacturing conformance, environmental performance and service ability. Flexibility could be measured in terms of product customization ability, volume flexibility, and mix flexibility.

Sampling – Measuring product modularity only makes sense in discrete manufacturing settings, not in process industries. Following the majority of studies referred to in this paper, the most likely candidates are the fabricated metal products, computer and electronics, electrical equipment, machinery and equipment, motor vehicle and other transport equipment, furniture and the plastics and, toys, and instrument industries.

REFERENCES

Abernathy, W. J. and Utterback, J. M. (1978), Patterns of industrial innovation, *Technology Review*, Vol. 80, No. 7, pp. 40-47

Arnheiter, E. D. and Harren, H. (2006), Quality management in a modular world, *The TQM Magazine*, Vol. 18, No. 1, pp. 87-96

Baldwin, C. Y. and Clark, K. B. (1997), Managing in an age of modularity, *Harvard Business Review*, Vol. 75, No. 5, pp. 84-93

Baldwin, C. Y. and Clark, K. B. (2000), *Design rules. Vol. 1: the power of modularity*, Cambridge (Mass.): MIT Press

Bierly III, P. E., Gallagher, S., and Spender, J. C. (2008), Innovation and learning in high-reliability organizations: A case study of United States and Russian nuclear attack submarines, *IEEE Transactions on Engineering Management,* Vol. 55, No. 3, pp. 393-408

Brusoni, S. and Prencipe, A. (2001), Unpacking the black box of modularity: Technologies, products and organizations, *Industrial Corporate Change,* Vol. 10, No. 1, pp. 179-205

Campagnolo, D. and Camuffo, A. (2010), The concept of modularity in management studies: A literature review, *Journal of Management Review,* Vol. 12, No. 3, pp. 259-283

Chesbrough, H. and Kusunoki, K. (2001), The modularity trap: Innovation, technology phase shifts, and the resulting limits of virtual organization. In: Nonaka, I. and Teece, D.J. *Managing Industrial Knowledge: Creation, transfer and Utilization*. London: Sage Publications, pp. 202-203

Chung, S., Han, J. K. and Sohn, Y. S. (2012), Technological expectation and consumer preferences for product form, *Journal of Business Research,* Vol. 65, No. 9, pp. 1290-1294

Danese, P. and Filippini, R. (2010), Modularity and the impact on new product development time performance: Investigating the moderating effects of supplier involvement and interfunctional integration, *International Journal of Operations & Production Management,* Vol. 30, No. 11, pp. 1191-1209

Danese, P. and Filippini, R. (2013), Direct and mediated effects of product modularity on product development time and product performance, *IEEE Transactions on Engineering Management,* Vol. 60, No. 2, pp. 260-271

Duray, R. (2004), Mass customizers' use of inventory, planning techniques and channel management, *Production Planning & Control: The Management of Operations,* Vol. 15, No. 4, pp. 412-421

Eom, J. (2008), Modularity and technological change: A primer and synthesis, *Asian Journal of Technology Innovation,* Vol. 16, No. 2, pp. 1-24

Ernst, D. (2005), Limits to modularity: Reflections on recent developments in chip design, *Industry and Innovation,* Vol. 12, No. 3, pp. 303-335

Ethiray, S. K. (2007), Allocation of inventive effort in complex product systems, *Strategic Management Journal,* Vol. 28, No. 6, pp. 563-584

Ethiray, S. K., Levinthal, D. and Roy, R. R. (2008), The dual role of modularity: Innovation and imitation, *Management Science,* Vol. 54, No. 5, pp. 939-955

Fine, C. H. (2000), Clockspeed-based strategies for supply chain design, *Production and Operations Management,* Vol. 9, No. 3, pp. 213-221

Garud, R. and Kumaraswamy, A (1993), Changing competitive dynamics in network industries: an exploration of Sun Microsystems' open systems strategy, *Strategic Management Journal,* Vol. 14, No. 5, pp. 351-369

Garud, R. and Kumaraswamy, A (1995), Technological and organizational designs for realizing economies and substitution, *Strategic Management Journal,* Vol. 16, pp. 93-109

Gershenson, J. K., Garad, G. J. and Zhang, Y. (2012), Product modularity: definitions and benefits, *Journal of Engineering Design,* Vol. 14, No. 3, pp. 295-313

Genba, K., Ogawa, H. and Kodama, F. (2005), Quantitative analysis of modularization in the automobile and PC industries, *Technology Analysis & Strategic Management,* Vol. 17, No. 2, pp. 231-245

Guo, K. and Gershenson, J. K. (2007), Discovering relationships between modularity and cost, *Journal of Intelligent Manufacturing,* Vol. 18, No. 1, pp. 143-157

Hansen, P. H. K. and Sun, H. (2011), Complexity in managing modularization, International conference on information management, innovation management and industrial engineering, Vol. 3., pp. 537-540

Henderson, R. M. (1992), Technological change and the management of architectural knowledge. In: Kochan, T. and Useem. M., *Transforming organisations,* Oxford: Oxford University Press

Hsuan, J. and Hansen, P. K. (2007), Platform development: Implications for portfolio management, *Gestão & Producão,* Vol. 14, No. 3, pp. 453-461

Jacobs, M., Vickery, S. K. and Droge, C. (2007), The effects of product modularity on competitive performance: Do integration relationships mediate the relationship? *International Journal of Operations & Production Management,* Vol. 27, No. 10, pp. 1046-1068

Jacobs, M., Droge, C. Vickery, S. K. and Calantone, R. (2011), Product and process modularity's effects on manufacturing agility and firm growth performance, *Journal of product innovation management,* Vol. 28, No.1, pp. 123-137

Lau Antonio, K. W., Yam, R. C. M. and Tang, E. (2007), The impacts of product modularity on competitive capabilities and performance: An empirical study, *International Journal of Production Economics,* Vol. 105, No. 1, pp. 1-20

Lau Antonio, K. W., Yam, R. C. M. and Tang, E. (2009), The complementarity of internal integration and product modularity: An empirical study of their interaction effect on competitive capabilities, *Journal of Engineering and Technology Management,* Vol. 26, No. 4, pp. 305-326

Mikkola, J. (2006), Capturing the degree of modularity embedded in product architectures, *International Journal of Product Innovation Management,* Vol. 23, No. 2, pp. 128-146

Mikkola, J. and Gassmann, O. (2003), Managing modularity of product architectures: Toward an integrated theory, *IEEE Transactions on Engineering Management,* Vol. 50, No. 2, pp. 204-218

Meyer, M. H. and Lehnerd, A. P. (1997), *The power of product platforms; Building value and cost leadership*, New York; Free Press

Orton, J. D. and Weick, K. E. (1990), Loosely coupled systems: A reconceptualization, *Academy of Management Review,* Vol. 15, No. 2, pp. 203-223

Pasche, M., Persson, M. and Löfsten, H. (2011), Effects of platforms on new product development projects, *International Journal of Production Management,* Vol. 31, No. 11, pp. 1144-1163

Pasche, M. and Sköld, M. (2012), Potential drawbacks of component commonality in product platform development, *International Journal of Automotive Technology and Management,* Vol. 12, No. 1, pp. 92-108

Pil, F. K. and Cohen, S. K. (2008), Modularity: Implications for imitation, innovation and sustained advantage, *Academy of Management Review,* Vol. 31, No. 4, pp. 995-1011

Sanchez, R. and Mahoney, J. T. (1996), Modularity, flexibility, and knowledge management in product and organization design, *Strategic Management Journal,* Vol. 17, pp. 63-76

Simon, H. A. (1962), The architecture of complexity, *Proceedings of the American Philosophical Society,* Vol. 106, No. 6, pp. 467-482

Ulrich (1995), The role of product architecture in the manufacturing firm, *Research Policy,* Vol. 24, No. 3, pp. 419-440

Ulrich, K. T. and Tung, K. (1991), Fundamentals of product modularity, *Issues in Design Manufacturing/Integration,* Vol. 39, pp. 73-77

Ulrich, K. T. and Eppinger, S. D. (2012), *Product design and development,* New York; McGraw-Hill

Watanabe, C. and Ane, B. K. (2004), Constructing a virtuous cycle of manufacturing agility: Concurrent roles of modularity of modularity in improving agility and reducing lead time, *Technovation,* Vol. 24, No. 7, pp. 573-583

Wheelwright, S. C. (1992), Creating project plans to focus product development, *Harvard Business Review,* Vol. 70, No. 2, pp. 70-82

Worren, N., Moore, K. and Cardona, P. (2002), Modularity, strategic flexibility, and firm performance: A study of the home appliance industry, *Strategic Management Journal,* Vol. 23, No. 12, pp. 1123-1140